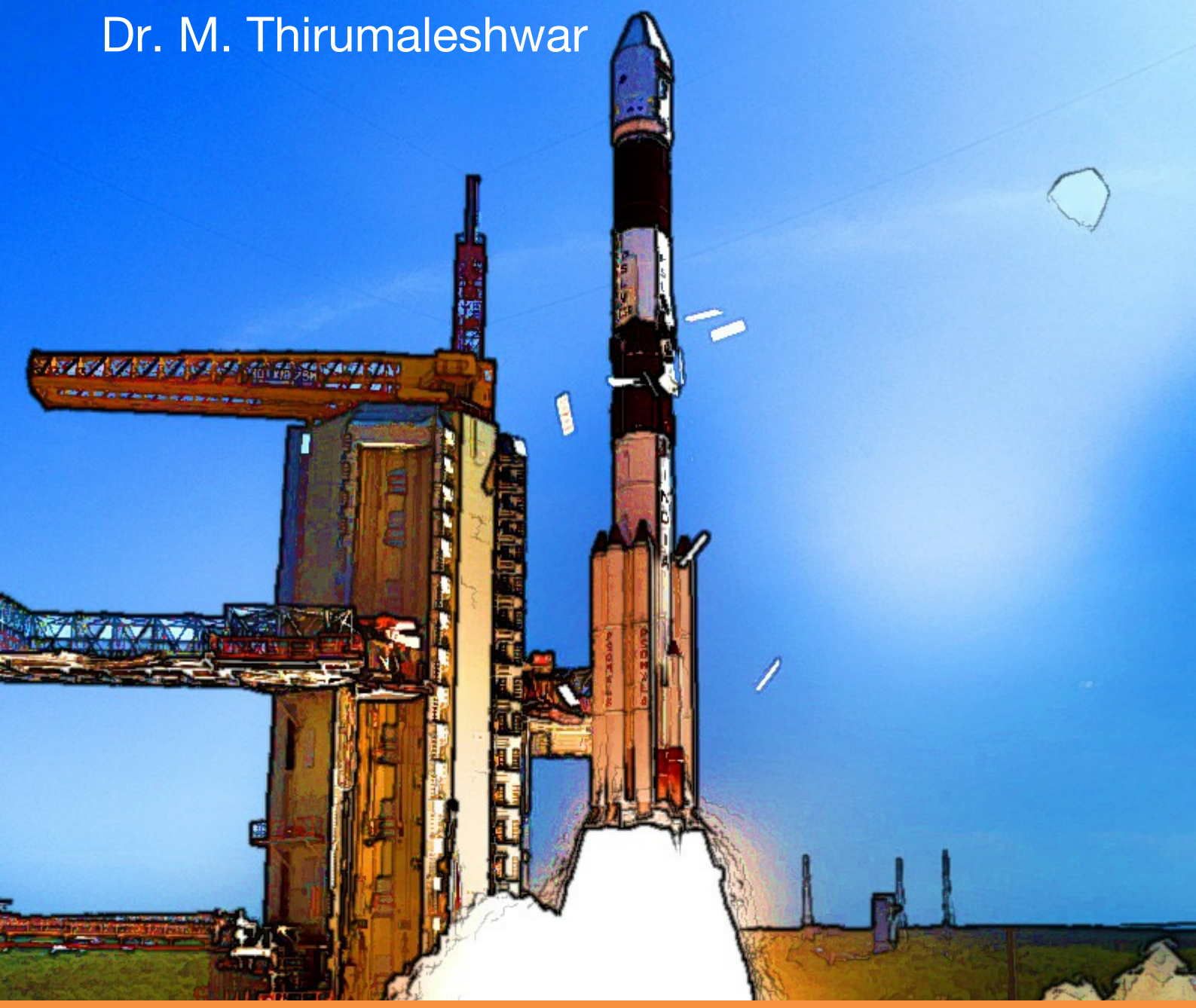
Cryogenic Engineering: Software Solutions: Part-VI

Vacuum Technology: Theory + Problems

Dr. M. Thirumaleshwar



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DR. M. THIRUMALESHWAR

CRYOGENIC ENGINEERING: SOFTWARE SOLUTIONS: PART-VI

VACUUM TECHNOLOGY: THEORY + PROBLEMS

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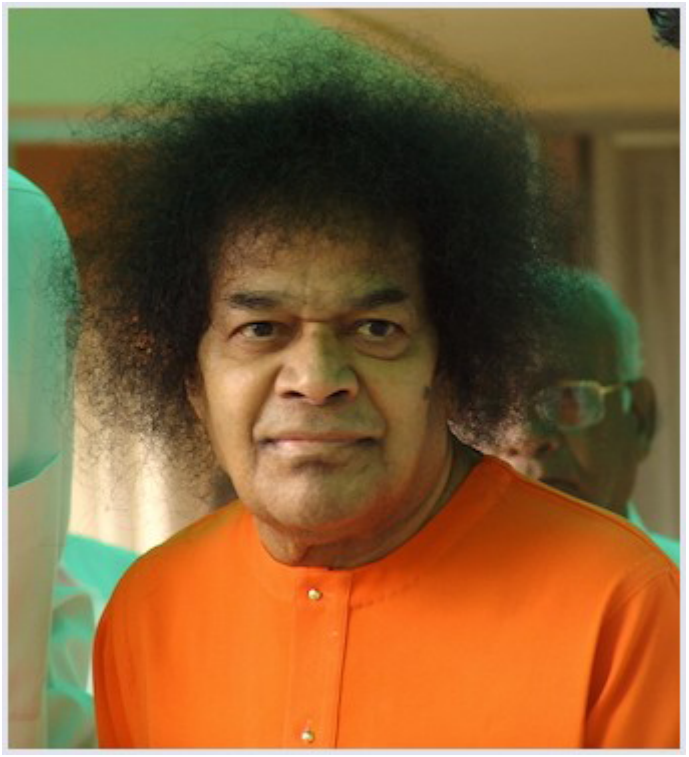
DEDICATION

This work is lovingly dedicated at the lotus feet of

Bhagavan Sri Sathya Sai Baba



"There is only one religion, the religion of Love.

There is only one caste, the caste of Humanity.

There is only one language, the language of the Heart.

There is only one God, He is Omnipresent."

"Help Ever, Hurt Never!"

– Bhagavan Sri Sathya Sai Baba

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PREFACE

This book, viz. **Cryogenic Engineering: Software solutions – Part-VI,** is the sixth in the series on **Cryogenic Engineering: Software Solutions.**

This book deals with the topics on **Vacuum Technology.**

This part, i.e. Part-VI, contains a brief summary of background theory, definitions and formulas and the problems solved with **Mathcad, Excel, EES, and GNU Octave (free software compatible with MATLAB)**

As with the Part-I, II, III, IV and V of the series, the focus is on the solutions of problems in Cryogenic engineering using software. *Only the essential theory and summary of equations required for calculations are given at the beginning of the chapter*.

Advantages of using computer software to solve problems are reiterated:

1. It helps in solving the problems fast and accurately
2. Parametric analysis (what – if analysis) and graphical visualization is done very easily. This helps in an in–depth analysis of the problem.
3. Once a particular type of problem is solved, it can be used as a *template* and solving similar problems later becomes extremely easy.
4. In addition, one can plot the data, curve fit, write functions for various properties or calculations and re-use them.
5. These possibilities create interest, curiosity and wonder in the minds of students and enthuse them to know more and work more.

In this book, following topics are dealt with:

1. **Importance of Vacuum Technlogy in Cryogenics, and Flow regimes in vacuum systems**
2. **System design aspects**
3. **Components of Vacuum systems**

Under *Importance of Vacuum Technlogy in Cryogenics, and Flow regimes in vacuum systems* we give a brief introduction and explain the various flow regimes in vacuum systems with reference to Knudsen Number.

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Under *System design aspects*, we deal with Conductances in vacuum systems – equations and Nomograms, Outgassing rates for materials, Calculation of pump down time etc.

Under *Components of Vacuum Systems*, we explain: Various types of vacuum pumps (with emphasis on Cryopumps) and vacuum gauges.

Several Functions are written and solved in Mathcad, Excel, GNU Octave (free software compatible with MATLAB, and EES to simplify the standard and most required calculations. Students, teachers, researchers and professionals may find them very useful.

Many numerical problems, mostly from the standard Ref.[1], are solved to illustrate the ease of calculations and graphing using these software.

S. I. Units are used throughout this book. Wide variety of worked examples presented in the book should be useful for those appearing for University, AMIE and Engineering Services examinations.

Acknowledgements: Firstly, I would like to **thank all my students**, who have been an inspiration to me in all my academic efforts.

I am thankful to **Dr. Thirumaleshwara Bhat**, Principal, Sri Madhwa Vadiraja Institute of Technology and Management, Bantakal, Udupi, for giving me support in my academic activities.

I gratefully remember my former colleagues at the Cryogenics section of Technical Physics Division, Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology, Indore for their sincere cooperation in a true spirit of team-work in all the projects that we undertook.

I particularly salute and admire the vision and foresight of former Heads of Technical Physics Division, BARC viz. late Mr. C. Ambasankaran, Mr. R.Y. Deshpande, Dr. S.R.Gowariker and late Mr. S.S.Ramamurthy in initiating and guiding many of the 'first of its kind' projects for Indian Space Research Organization (ISRO), wherein as a member of the Cryogenics section, this author was deeply involved in the design and execution of the cryogenic aspects of the projects.

I am especially grateful to Prof. R.G.Scurlock, former Director of Institute of Cryogenics, University of Southampton, (U. K.) for writing a message for the Part-I of this series.

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It was indeed gracious of my former Professor, under whom I studied for M.Sc. in Cryogenics at the University of Southampton, U.K. during 1970 – 72, and later worked as a Visiting Research Fellow during 1993-94, to honor me by writing this message.

My special thanks to **Bookboon.com** for publishing this *free ebook*. **Ms Karin Jakobsen** and the editorial staff have been most patient and helpful.

Finally, I would like to express my sincere thanks and appreciation to my **wife, Kala,** who, as usual, has given me continuous support, help and encouragement in all my academic activities, making many silent sacrifices.

M. Thirumaleshwar

March, 2020

Email: tmuliya@rediffmail.com

***Note:* Along with this book, a ZIP file is also available for *free download*.**

It contains:

1. Many 'stand alone' EXE files, written in EES to make various calculations explained in this chapter.
2. Excel worksheets to make conductance and pump down calculations. Just plug-in the Input data, and you should be able to see the outputs immediately. Calculation cells are protected so that the user does not erase them inadvertently.

Two Appendixes are included at the end of this ebook

Appendix-I gives the Matlab compatible m-files written in free, GNU Octave software (Ref: https://www.octave.org**)**

Appendix-II gives a copy of a paper on design of Thermovacuum chambers, by this Author, published in the Intl. Journal: CRYOGENICS, Nov. 1978.

All these should be of great use for students, teachers and researchers for quick verification of their design calculations.

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ABOUT THE AUTHOR

Dr. M. Thirumaleshwar graduated in Mechanical Engineering from Karnataka Regional Engineering College, Surathkal, Karnataka, India, in the year 1965. He obtained M.Sc (cryogenics) from University of Southampton, U.K. and Ph.D.(cryogenics) from Indian Institute of Science, Bangalore, India.

He is a Fellow of Institution of Engineers (India), Life Member, Indian Society for Technical Education, and a Foundation Fellow of Indian Cryogenics Council.

He has worked in India and abroad on large projects in the areas involving heat transfer, fluid flow, vacuum system design, cryo-pumping etc.

He worked as Head of Cryogenics Section in Bhabha Atomic Research Centre (BARC), Bombay and Centre for Advanced Technology (CAT), Indore, from 1966 to 1992.

He worked as Guest Collaborator with Superconducting Super Collider Laboratory of Universities Research Association, in Dallas, USA from 1990 to 1993.

He also worked at the Institute of Cryogenics, Southampton, U.K. as a Visiting Research Fellow from 1993 to 1994.

He was Head of the Dept. of Mechanical Engineering, Fr. Conceicao Rodrigues Institute of Technology, Vashi, Navi Mumbai, India for eight years.

He also worked as Head of Dept. of Mechanical Engineering and Civil Engineering, and then as Principal, Vivekananda College of Engineering and Technology, Puttur (D.K.), India.

He was Professor and coordinator of Post-graduate program in the Dept. of Mechanical Engineering in St. Joseph Engineering College, Vamanjoor, Mangalore, India.

A book entitled **"Fundamentals of Heat and Mass Transfer"** authored by him and published by M/s Pearson Education, India (2006) **has been adopted as a Text book** for third year engineering students by the Visweswaraya Technological University (V.T.U.), Belgaum, India.

He has authored a ***free e-book*** **series** entitled **"Software Solutions to Problems on Heat Transfer"** wherein problems are solved using 4 software viz. Mathcad, EES, FEHT and EXCEL. This book, containing about 2750 pages, is presented in 9 parts and all the 9 parts can be downloaded *for free* from www.bookboon.com

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He has also authored ***free e-books*** **on Thermodynamics** entitled **"Basic Thermodynamics: Software Solutions" and "Applied Thermodynamics: Software Solutions"** wherein problems are solved using 3 software viz. Mathcad, EES, and TEST. Each of these titles is presented in 5 parts and all the books can be downloaded *for free* from www.bookboon.com

In addition, he has authored following two useful *free ebooks*:

i. Applied Thermodynamics: Software Solutions: Vapor compression Refrigeration cycle + Problems (Mathcad)
http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-ebook
ii. Applied Thermodynamics: Software Solutions: Vapor Power cycles (Rankine cycle) + Problems (Mathcad)
http://bookboon.com/en/applied-thermodynamics-software-solutions-vapor-po-ebook

His earlier *free ebooks in this* **Cryogenic Engineering series**, viz. **Cryogenic Engineering: Software Solutions – Parts-I, II-A and II-B, III-A, III-B, IV and V-A&B** have already been published by Bookboon.

He has also authored **three motivational, free ebooks**, published by www.bookboon.com, entitled as follows:

1. Towards Excellence… How to Study (A Guide book to Students)
2. Towards Excellence… How to teach (A guide book to Teachers)
3. Towards Excellence… Seminars, GD's and Personal Interviews

Dr. M. Thirumaleshwar has attended several National and International conferences and has more than 50 publications to his credit.

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ABOUT THE SOFTWARE USED

Following software are used while solving problems in this book series:

1. Mathcad 7 and Mathcad 15 (Ref: www.ptc.com)
2. Engineering Equation Solver (EES) (Ref: www.fchart.com),
3. MS Excel, which normally comes bundled with every PC, and
4. GNU Octave, which is a free software compatible with Matlab

For a brief introduction to Mathcad, EES and EXCEL see the chapter 1 of the following *free ebook* by the author:

"Software Solutions to Problems on Heat Transfer – CONDUCTION-Part-I":
http://bookboon.com/en/software-solutions-to-problems-on-heat-transfer-ebook

GNU Octave may be freely downloaded from:

https://www.octave.org

Many good reference books/tutorials on GNU Octave are available for free, on-line.

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7 VACUUM TECHNOLOGY

Learning objectives

1. In this chapter, topics on 'Importance of Vacuum Technlogy in Cryogenics, and Flow regimes in vacuum systems, System design aspects, and Components of Vacuum systems' are dealt with.
2. First, importance of Vacuum Technology in Cryogenics and various flow regimes in vacuum systems with reference to Knudsen Number are explained.
3. Next, Vacuum system design aspects are taken up. And, calculations of Conductances for various elements and pump down times of vacuum systems and Nomograms for their quick calculations are presented.
4. Various components of Vacuum systems such as different types of Vacuum pumps and vacuum gauges are explained.
5. Several Functions/ Procedures are written, and problems solved, in Mathcad, Excel, Engineering Equation Solver (EES) and GNU Octave (free software compatible with Matlab), which greatly simplify the calculations.
6. **A free ZIP file accompanying this ebook contains many 'stand alone' EXE files written in EES, and also EXCEL calculation worksheets. These should be very much useful to teachers, students and researchers working in this field to quickly make/ verify their design calculations.**

7.1 INTRODUCTION: [REF: 1 TO 4]

Importance of Vacuum Technology: Cryogenics and Vacuum Technology are closely connected:

Vacuum is used as an effective insulation in dewar vessels and cryostats. Temperatures lower than the boiling points are obtained by pumping over cryogenic fluids. Vacuum pumps are used in He3 – He4 dilution refrigerators, used to get temperatures in milli-Kelvin range.

And, cryogenic fluid, such as LN2 is used in 'cold traps' to eliminate moisture, CO2 etc in vacuum systems. Also, ultra-high vacuum is obtained with Cryopumping where the gases are 'frozen out' using cryogenic fluids. Space simulation chambers use LN2 cooled 'shrouds' to get low temperatures to simulate the space - conditions to test the electronic components of satellites sent to outer space.

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7.2 FLOW REGIMES IN VACUUM SYSTEMS

Preliminary:

a. In Vacuum technology, popular **unit of pressure** is: 1 torr = 1 mm of Hg.
Pressure ranges for different ranges of vacuum are given below:
Ref: https://en.wikipedia.org/wiki/Vacuum#Uses

Pressure ranges of each quality of vacuum in different units

Vacuum quality	Torr	Pa	Atmosphere
Atmospheric pressure	760	1.013×10^{5}	1
Low vacuum	760 to 25	1×10^{5} to 3×10^{3}	9.87×10^{-1} to 3×10^{-2}
Medium vacuum	25 to 1×10^{-3}	3×10^{3} to 1×10^{-1}	3×10^{-2} to 9.87×10^{-7}
High vacuum	1×10^{-3} to 1×10^{-9}	1×10^{-1} to 1×10^{-7}	9.87×10^{-7} to 9.87×10^{-13}
Ultra high vacuum	1×10^{-9} to 1×10^{-12}	1×10^{-7} to 1×10^{-10}	9.87×10^{-13} to 9.87×10^{-16}
Extremely high vacuum	$< 1 \times 10^{-12}$	$< 1 \times 10^{-10}$	$< 9.87 \times 10^{-16}$
Outer space	1×10^{-6} to $< 1 \times 10^{-17}$	1×10^{-4} to $< 3 \times 10^{-15}$	9.87×10^{-10} to $< 2.96 \times 10^{-20}$
Perfect vacuum	0	0	0

b. **Pressure conversions to different units are given below:**
Ref:
https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/definition-of-vacuum/

	Pa	bar	hPa	µbar	Torr	micron	atm	at	mm WS	psi	psf
Pa	1	$1 \cdot 10^{-5}$	$1 \cdot 10^{-2}$	10	$7.5 \cdot 10^{-3}$	7.5	$9.87 \cdot 10^{-6}$	$1.02 \cdot 10^{-5}$	0.102	$1.45 \cdot 10^{-4}$	$2.09 \cdot 10^{-2}$
bar	$1 \cdot 10^{5}$	1	$1 \cdot 10^{3}$	$1 \cdot 10^{6}$	750	$7.5 \cdot 10^{5}$	0.987	1.02	$1.02 \cdot 10^{4}$	14.5	$2.09 \cdot 10^{3}$
hPa	100	$1 \cdot 10^{-3}$	1	1,000	0.75	750	$9.87 \cdot 10^{-4}$	$1.02 \cdot 10^{-3}$	10.2	$1.45 \cdot 10^{-2}$	2.09
µbar	0.1	$1 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	1	$7.5 \cdot 10^{-4}$	0.75	$9.87 \cdot 10^{-7}$	$1.02 \cdot 10^{-6}$	$1.02 \cdot 10^{-2}$	$1.45 \cdot 10^{-5}$	$2.09 \cdot 10^{-3}$
Torr	$1.33 \cdot 10^{2}$	$1.33 \cdot 10^{-3}$	1.33	1,330	1	1,000	$1.32 \cdot 10^{-3}$	$1.36 \cdot 10^{-3}$	13.6	$1.93 \cdot 10^{-2}$	2.78
micron	0.133	$1.33 \cdot 10^{-6}$	$1.33 \cdot 10^{-3}$	1.33	$1 \cdot 10^{-3}$	1	$1.32 \cdot 10^{-6}$	$1.36 \cdot 10^{-6}$	$1.36 \cdot 10^{-2}$	$1.93 \cdot 10^{-5}$	$2.78 \cdot 10^{-3}$
atm	$1.01 \cdot 10^{5}$	1.013	1,013	$1.01 \cdot 10^{6}$	760	$7.6 \cdot 10^{5}$	1	1.03	$1.03 \cdot 10^{4}$	14.7	$2.12 \cdot 10^{3}$
at	$9.81 \cdot 10^{4}$	0.981	981	$9.81 \cdot 10^{5}$	735.6	$7.36 \cdot 10^{5}$	0.968	1	$1 \cdot 10^{4}$	14.2	$2.04 \cdot 10^{3}$
mm WS	9.81	$9.81 \cdot 10^{-5}$	$9.81 \cdot 10^{-2}$	98.1	$7.36 \cdot 10^{-2}$	73.6	$9.68 \cdot 10^{-5}$	$1 \cdot 10^{-4}$	1	$1.42 \cdot 10^{-3}$	0.204
psi	$6.89 \cdot 10^{3}$	$6.89 \cdot 10^{-2}$	68.9	$6.89 \cdot 10^{4}$	51.71	$5.17 \cdot 10^{4}$	$6.8 \cdot 10^{-2}$	$7.02 \cdot 10^{-2}$	702	1	144
psf	47.8	$4.78 \cdot 10^{-4}$	0.478	478	0.359	359	$4.72 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$	4.87	$6.94 \cdot 10^{-3}$	1

Remember: 1 torr = 133 Pa.

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c. **Mean free path**: This is average distance travelled by a moving particle between successive impacts (collisions). Mean free path of a gas is related to its viscosity, and is given by:

$$\lambda = \frac{\mu}{p} \cdot \pi \cdot \left(\frac{R_u \cdot T}{2 \cdot M} \right)^{\frac{1}{2}}$$

where p is the gas pressure, R_u is Universal gas constant, T is absolute temp, and M is the molecular weight.

The following table lists some **typical values for air** at different pressures at room temperature. (Ref: https://en.m.wikipedia.org/wiki/Mean_free_path)

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Vacuum range	Pressure in hPa (mbar)	Pressure in mmHg (Torr)	number density (Molecules / cm^3)	number density (Molecules / m^3)	Mean free path
Ambient pressure	1013	759.8	2.7×10^{19}	2.7×10^{25}	68 nm[2]
Low vacuum	$300 - 1$	$220 - 8\times10^{-1}$	$10^{19} - 10^{16}$	$10^{25} - 10^{22}$	0.1 – 100 µm
Medium vacuum	$1 - 10^{-3}$	$8\times10^{-1} - 8\times10^{-4}$	$10^{16} - 10^{13}$	$10^{22} - 10^{19}$	0.1 – 100 mm
High vacuum	$10^{-3} - 10^{-7}$	$8\times10^{-4} - 8\times10^{-8}$	$10^{13} - 10^{9}$	$10^{19} - 10^{15}$	10 cm – 1 km
Ultra-high vacuum	$10^{-7} - 10^{-12}$	$8\times10^{-8} - 8\times10^{-13}$	$10^{9} - 10^{4}$	$10^{15} - 10^{10}$	1 km – 10^5 km
Extremely high vacuum	$<10^{-12}$	$<8\times10^{-13}$	$<10^{4}$	$<10^{10}$	$>10^5$ km

Flow regimes: At ordinary pressures, flow regimes are determined by Reynolds Number, defined as:

$$Re = \frac{D \cdot v \cdot \rho}{\mu}$$

where D = diameter, v = velocity of flow, ρ is the density and μ is the viscosity.

And, flow regimes at ordinary pressures are:

1. Laminar flow …. Re < 2300
2. Transition flow ….2300 < Re < 3000
3. Turbulent flow …. Re > 3000

Flow regimes in vacuum conditions:

Here, Knudsen number, NKn is the controlling dimensionless number which determines the flow regime.

Knudsen number is defined as:

$$Kn = \frac{\lambda}{D}$$

where λ is the mean free path, and D is the characteristic dimension (i.e. diameter of a circular tube, or the distance between the plates for two parallel plates).

In terms of NKn the flow regimes in vacuum are:

1. Continuum flow …. $N_{Kn} < 0.01$
2. Mixed flow … $0.01 < N_{Kn} < 1$
3. Free Molecular flow … $N_{Kn} > 1$

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Using the definition for mean free path, we can write for Knudsen number:

$$Kn = \frac{\mu}{p \cdot D} \cdot \left(\frac{\pi \cdot R_u \cdot T}{2 \cdot M} \right)^{\frac{1}{2}}$$

7.3 CONDUCTANCE IN VACUUM SYSTEMS

The defining equation for conductance in vacuum technology is:

(Ref: https://en.wikipedia.org/wiki/Fluid_conductance)

$$Q = (P1 - P2) \cdot C$$

Here:

Q is the total **throughput**, usually, by convention, **not measured as a mass throughput** but rather as a pressure throughput and ***having units of pressure times volume per second***, P1, P2 are the upstream and downstream pressures, and C is the conductance, having units of volume/time, which are the same units as pumping speed for a vacuum pump.

This definition proves useful in vacuum systems because under conditions of rarefied gas flow, the conductance of various structures is usually constant, and the overall conductance of a complex network of pipes, orifices and other conveyances can be found in direct analogy to a resistive electrical circuit.

For example, the ***conductance of a simple orifice*** is:

C = 15. d^2 liters/sec, where d is measured in centimetres.

Conversion table for units of throughput:

Ref:https://www.pfeiffer-vacuum.com/en/know-how/introduction-to-vacuum-technology/fundamentals/definition-of-vacuum/

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	Pa m^3/s = W	mbar l/s	Torr l/s	atm cm^3/s	lusec	sccm	slm	Mol/s
Pa m^3/s	1	10	7.5	9.87	$7.5 \cdot 10^3$	592	0.592	$4.41 \cdot 10^{-4}$
mbar l/s	0.1	1	0.75	0.987	750	59.2	$5.92 \cdot 10^{-2}$	$4.41 \cdot 10^{-5}$
Torr l/s	0.133	1.33	1	1.32	1,000	78.9	$7.89 \cdot 10^{-2}$	$5.85 \cdot 10^{-5}$
atm cm^3/s	0.101	1.01	0.76	1	760	59.8	$5.98 \cdot 10^{-2}$	$4.45 \cdot 10^{-5}$
lusec	$1.33 \cdot 10^{-4}$	$1.33 \cdot 10^{-3}$	10-3	$1.32 \cdot 10^{-3}$	1	$7.89 \cdot 10^{-2}$	$7.89 \cdot 10^{-5}$	$5.86 \cdot 10^{-8}$
sccm	$1.69 \cdot 10^{-3}$	$1.69 \cdot 10^{-2}$	$1.27 \cdot 10^{-2}$	$1.67 \cdot 10^{-2}$	12.7	1	10-3	$7.45 \cdot 10^{-7}$
slm	1.69	16.9	12.7	16.7	$1.27 \cdot 10^4$	1,000	1	$7.45 \cdot 10^{-4}$
Mol/s	$2.27 \cdot 10^3$	$2.27 \cdot 10^4$	$1.7 \cdot 10^4$	$2.24 \cdot 10^4$	$1.7 \cdot 10^7$	$1.34 \cdot 10^6$	$1.34 \cdot 10^3$	1

The effective pumping speed is always less than the rated inlet speed of the pump due to the resistance (inverse of conductance) offered by baffles, valves, cold traps, piping etc.

Calculating Conductance:

$$C = \frac{Q}{\Delta p} = \frac{m\_dot}{\Delta \rho}$$

where Q is throughput, ρ is gas density, m_dot is mass flow rate.

Conductances for a long tube (L / D > 30) are given as follows [1]:

1. Laminar continuum flow:

$$C = \frac{\pi \cdot D^4 \cdot p\_bar}{128 \cdot \mu \cdot L}$$

where, p_bar = (p1 + p2)/2

2. Mixed flow:

$$C = \left(\frac{\pi \cdot D^4 \cdot p\_bar}{128 \cdot \mu \cdot L} \right) \cdot \left[1 + \left(\frac{8 \cdot \mu}{p\_bar \cdot D} \right) \cdot \left[\left(\frac{\pi \cdot R_u \cdot T}{2 \cdot M} \right)^{\frac{1}{2}} \right] \right]$$

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3. Free molecular flow:

$$C=\left[\left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}}\right] \cdot \frac{D^3}{L}$$

Conductances of some elements of a Vacuum system:

In the following formulas, T = temp (K), M = Mol. Wt. (kg/kmol)

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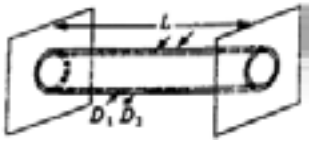
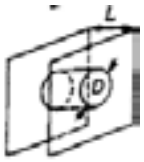
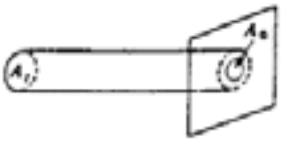
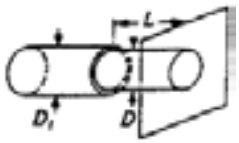
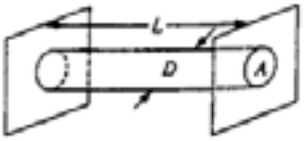
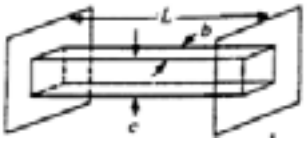
Geometry	Sketch	C_mol (lit/s)	C_mol_air25C (lit/s)
Orifice, (Area = A, cm^2)		$C = 3.64A\left(\frac{T}{M}\right)^{1/2}$	$= 11.7A$
Long tube, (L,D in cm, A in cm^2)		$C = 6.18\frac{A^2}{DL}\left(\frac{T}{M}\right)^{1/2}$	$= 12.2\frac{D^3}{L}$
Annular tube (D1,D2,L in cm)		$C = 3.81\frac{D^3}{L}\left(\frac{T}{M}\right)^{1/2}$	$= 12.2\frac{(D_2 - D_1)^2(D_2 + D_1)}{L}$
Rectangular tube (b,c,L in cm)		$C = 9.70\frac{b^2c^2}{(b + c)L}\left(\frac{T}{M}\right)^{1/2}$	$= 31.1\frac{b^2c^2}{(b + c)L}$
Short tube (L, D in cm)		$C = 2.85D^2\left(\frac{T}{M}\right)^{1/2}\left(\frac{1}{1 + 3L/4D}\right)$	$= 9.14\frac{D^2}{1 + 3L/4D}$
Aperture at the end of tube (D,D_t,L in cm)		$C = 3.64\left(\frac{T}{M}\right)^{1/2}\left(\frac{A}{1 - (A/A_t)}\right)$	$= \frac{11.7A_0}{1 - A_0/A_t}$
Short, annular tube (D_t,D,L in cm)		$C = 3.81\frac{D^3}{L}\left(\frac{T}{M}\right)^{1/2}\left(\frac{1}{1 + \frac{4D}{3L}\left(1 - \frac{D_t^2}{D^2}\right)}\right)$	$= \frac{12.2D^3}{L\left[1 + \frac{4D}{3L}\left(1 - \frac{D_t^2}{D^2}\right)\right]}$

Conductances in series and parallel:

When individual elements are in **series**, the overall conductance is given by:

$$\frac{1}{C_o} = \sum_i \frac{1}{C_i}$$

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Typical example of conductance in series is: a vacuum pump connected to the chamber through piping, valves, cold trap etc. Then, the pumping speed (S) at the chamber, connected by a conductance (C) to a pump of pumping speed (S_p), is calculated by the formula:

$$\frac{1}{S}=\frac{1}{S_p}+\frac{1}{C}$$

And, when the elements are in **parallel**, overall conductance is given by:

$$C_o=\sum_i C_i$$

As an example of conductance in series: consider free molecular flow through a 'short' tube. The overall conductance is a combination of the conductance of the tube itself and the conductance of the orifice at the end of the tube. If the tube opens in to a large vessel (i.e. (A2 / A1) = 0), total conductance is:

$$\frac{1}{C_o}=\frac{1}{C_1}+\frac{1}{C_2}$$

$$\frac{1}{C_o}=\left(\frac{32\cdot M}{\pi\cdot R_u\cdot T}\right)^{\frac{1}{2}}\cdot\left(\frac{1}{D^2}\right)+\left(\frac{18\cdot M}{\pi\cdot R_u\cdot T}\right)^{\frac{1}{2}}\cdot\left(\frac{L}{D^3}\right)$$

Solving, we get (for a 'short' tube):

$$C_o=\frac{\left(\frac{\pi\cdot R_u\cdot T}{18\cdot M}\right)^{\frac{1}{2}}\cdot D^2}{\frac{L}{D}+\frac{4}{3}}$$

(Note: Arbitrarily defining 'short' tube as one for which conductance given by the above equation differs from the conductance of a 'long' tube (defined earlier), by 5%, we get (L/D) = 27. So, we say that when ratio (L/D) < 30, the tube may be considered as a 'short' tube.)

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Example7.1. Determine the throughput through a vacuum system consisting of a 500 mm long section of a 50 mm ID tube connected in series to a 375 mm long section of a 25 mm ID tube. The 50 mm tube is connected at a large vessel in which the pressure is 100 mPa (7.5 x 10^{-4} torr), and the pressure at the exit of the 25 mm tube is 5 mPa (3.75 x 10^{-5} torr). The temperature of the air (M = 28.95 g/mol) flowing through the system is 300 K (540°R).

Note: This is a worked out problem in Ref.[1], i.e. Barron, p 436.

Solution:

First, let us write Mathcad Functions for mean free path (λ) and Knudsen number(Kn):

$$\lambda(p,\mu,T,M) := \frac{\mu}{p}\cdot\left(\frac{\pi\cdot 8314.34\cdot T}{2\cdot M}\right)^{\frac{1}{2}}$$ ....Function for Mean free path

$$Kn(p,\mu,T,M,D) := \frac{\lambda(p,\mu,T,M)}{D}$$ ....Function for Knudsen Number

In the above Functions: μ = dyn. visc in Pa-s; p = pressure, Pa; T = temp, K; M = Mol. wt, kg/kmol; Universal gas const, Ru = 8314.34 J/kmol.K; D = Diameter of tube, m

For air at 300 K, we have:

$T := 300$ K

$\mu := 18.47\cdot 10^{-6}$ Pa

$R_u := 8314.34$ J/kg.K

$M := 28.97$ kJ/kmol

$p := 0.1$ Pa

$D := 0.05$ m

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Then, we have:

$\lambda(p,\mu,T,M) = 0.06792$ m .... mean free path at a pressure of p = 0.1 Pa

$Kn(p,\mu,T,M,D) = 1.35849$ ...Knudsen number = λ/D

Here, Kn > 1. Therefore, it is Free mol. flow in the 50 mm dia tube.

Conductance of 50mm dia, 500 mm long tube:

L/D = 10.(since L = 500 mm). So, we use eqn :

$$C2 := \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}} \cdot \left(\frac{D^2}{10 + \frac{4}{3}}\right)$$ i.e. $C2 = 0.02704$ m^3/s

i.e. $C2 := 27.04$ lit/s

Similarly for 25 mm tube of 375 mm length, conductance is determined from:

$D1 := 0.025$ m $L1 := 0.375$ m $D2 := 0.05$ m

$$C1 := \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}} \cdot \left[\frac{D1^2}{\frac{L1}{D1} + \frac{4}{3} \cdot \left(1 - \frac{D1^2}{D2^2}\right)}\right]$$

i.e. $C1 = 4.78849 \cdot 10^{-3}$ m^3/s

i.e. $C1 := 4.79$ lit/s

Then, overall conductance of these two tubes in series is:

$$C_o := \left(\frac{1}{C2} + \frac{1}{C1}\right)^{-1}$$ i.e. $C_o = 4.06917$ lit/s

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Then, throughput:

$Q = C_o \cdot \Delta p$

i.e. $Q := C_o \cdot (0.1 - 0.005)$

i.e. $Q = 0.38657$ Pa.lit/s

i.e. $Q := 0.38659 \cdot 10^{-3}$ Pa-m^3/s

This Q corresponds to a mass flow rate of:

$m\_dot := \frac{Q \cdot M}{R_u \cdot T}$ i.e. $m\_dot = 4.49004 \cdot 10^{-9}$ kg/s =4.490 µg/s

---

Conductance calculations using Dushman's table:

(Ref: Reprinted from page 99 of *Scientific Foundations of Vacuum Technique* by Saul Dushman 2nd edition (J.J. Laffery - editor), John Wiley & sons, 1962.)

This table gives the conductance (lit/s) of air at 25 C in Free molecular flow, in a tube of radius 'a' (cm) and length 'L' (cm).

Dushman's Table is shown below:

a (cm)	Conductance of tube of air at 25°C (liters per second)							
	L/a = 0	1	2	4	8	12	16	30
0.1	0.367	0.246	0.188	0.132	0.085	0.063	0.050	0.029
0.2	1.466	0.986	0.753	0.527	0.340	0.252	0.200	0.117
0.3	3.300	2.217	1.664	1.184	0.764	0.567	0.451	0.263
0.4	5.866	3.943	3.013	2.106	1.358	1.008	0.802	0.468
0.5	9.166	6.160	4.708	3.291	2.122	1.575	1.253	0.731
0.6	13.200	8.872	6.779	4.739	3.057	2.269	1.805	1.052
0.7	17.970	12.080	9.228	6.449	4.161	3.088	2.457	1.432
0.8	23.470	15.770	12.050	8.424	5.436	4.033	3.208	1.871
0.9	29.700	19.960	15.250	10.660	6.879	5.105	4.061	2.368
1.0	36.660	24.640	18.830	13.160	8.492	6.302	5.013	2.922
2.0	146.600	98.560	75.340	52.650	33.970	25.210	20.050	11.690
3.0	330.000	221.700	166.400	118.400	76.420	56.710	45.110	26.300
4.0	586.600	394.300	301.300	210.600	135.800	100.800	80.210	46.770
5.0	916.600	616.000	470.800	329.100	212.200	157.500	125.300	73.100
6.0	1,320.000	887.200	677.900	473.900	305.700	226.900	180.500	105.200
7.0	1,797.000	1,208.000	922.800	644.900	416.100	308.800	245.700	143.200
8.0	2,347.000	1,577.000	1,205.000	842.400	543.600	403.300	320.800	187.100
9.0	2,970.000	1,996.000	1,525.000	1,066.000	687.900	510.500	406.100	236.800
10.0	3,666.000	2,464.000	1,883.000	1,316.000	849.200	630.200	501.300	292.200

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In the above Table, first column gives the radius, 'a'. Second column gives the conductance for air at 25 C in molecular flow for an **orifice**. Next 7 columns give free molecular conductances for air at 25 C, for tubes of (L/a) ratios of 1, 2, 4, 8, 12, 16 and 30 respectively. One can do linear interpolation for conductances for values of 'a' and (L/a) not given in the Table.

Some Mathcad functions for conductances from this table will be shown later.

Following points may be noted:

(Ref: https://www.lesker.com/newweb/technical_info/conductance_calc.cfm)

- For tubes with *right-angle bends*, measure 'L' as the shortest distance shown (see drawing on the right). Calculate the conductance from the table as if the tube were straight, then divide the conductance by 2 for every right-angle bend.
- For tubes with *rectangular or square cross-section* (or even the annulus between two tubes), calculate the open area and find the radius of a cylindrical tube with an equal open area. Calculate the conductance of this 'equivalent tube' using Dushman's table.
- If the *diameter changes along the length of the tube*, use the smallest diameter to calculate 'a'.

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7.4 PROGRAMS TO CALCULATE CONDUCTANCES

7.4.1 EXCEL PROGRAMS

Ref for eqns.: Leybolds Fundamentals:

Conductance of not too short tube (l/D > 10) in Laminar flow (i.e. d * p_bar >= 0.6 mbar.cm), for Air at 20 C:

C = 135 *(d^4/L)*p_bar

Input:	d	1	cm
	L	12	cm
	p_bar	2	mbar
Check:	d * p_bar=	2	mbar.cm
Output:	C_lam	22.5	lit/s

Conductance of not too short tube (L/D > 10) in mol. flow (i.e. d * p_bar <= 0.01 mbar.cm), for Air at 20 C:

C = 12.1 * d^3 /L

Input:	d	0.5	cm
	l	8	cm
	p_bar	0.01	mbar
Check:	d * p_bar=	0.005	mbar.cm
Output:	C_mol	0.189063	lit/s

Conductance of not too short tube (L/D > 10) in transition flow (i.e. 0.01 < d * p_bar < 0.6 mbar.cm), for Air at 20 C:

C = 135 * (d^4 /L)* p_bar + 12.1 * d^3 / L * (1 + 192 * d * p_bar)/ (1 + 237 * d * p_bar)

Input:	d	1	cm
	L	10	cm
	p_bar	0.5	mbar
Check:	d * p_bar=	0.5	mbar.cm
Output:	C_trans	7.732176	lit/s

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Conductance of an Orifice of dia, d (cm) in mol. flow, for Air at 20 C:			
C_orif_mol = 11.6 * A			
Input:	d	1	cm
	A	0.785398	cm^2
Output:	C_mol_orif	9.110619	lit/s

Conductance of an Orifice of dia, d (cm) in visc. flow, with (p2/p1) = 0, for Air at 20 C:			
C_orif_visc = 20 * A			
Input:	d	1	cm
	A	0.785398	cm^2
Output:	C_mol_orif	15.70796	lit/s

Note: Above Formulas are for Air at 20 C.

1mbar = 100 Pa = 0.75 torr

For other gases, use multiplication factors from the following Table:

Gas (20 °C)	Molecular flow	Laminar flow
Air	1.00	1.00
Oxygen	0.947	0.91
Neon	1.013	1.05
Helium	2.64	0.92
Hydrogen	3.77	2.07
Carbon dioxide	0.808	1.26
Water vapor	1.263	1.73

We can also write a single VBA program to find out the conductance for air at 20 C, flowing in a pipe (D, L in cm), with an average pressure, p_avg (mbar), depending upon the flow regime.

Following is the VBA program:

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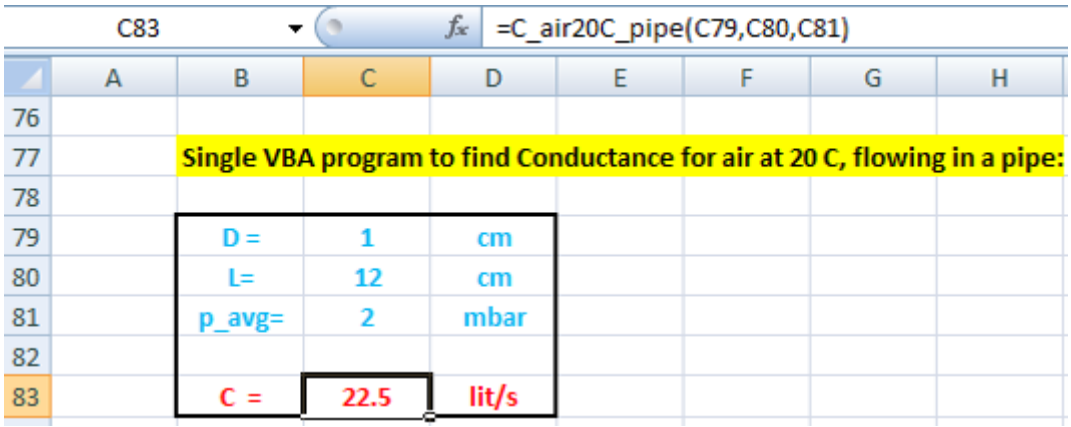
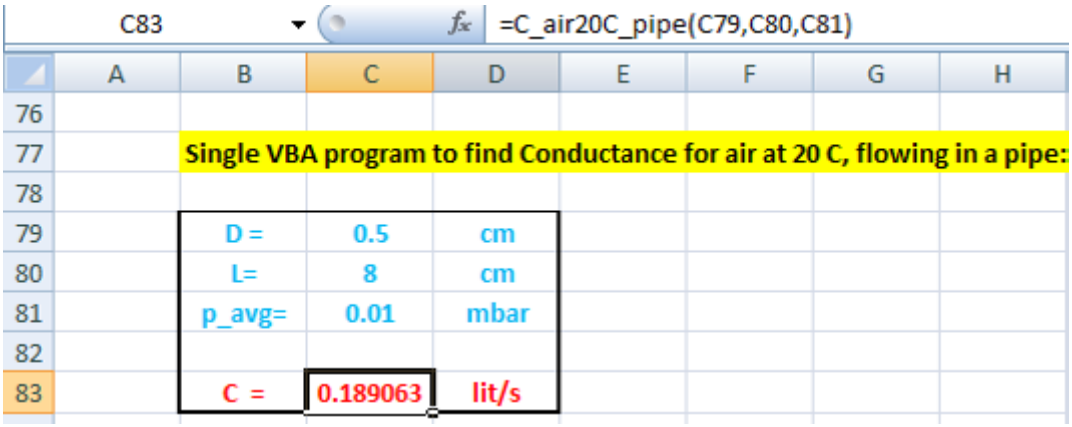
```
Function C_air20C_pipe(D As Double, L As Double, p_avg As Double) As Double
'Gives the conductance (lit/s),for air at 20 C flowing in a long pipe,D,L in cm, p_avg in mbar
If (D * p_avg) >= 0.6 Then
     C_air20C_pipe = 135 * (D ^ 4 / L) * p_avg
ElseIf (D * p_avg) <= 0.01 Then
     C_air20C_pipe = 12.1 * (D ^ 3 / L)
ElseIf 0.01 < (D * p_avg) < 0.6 Then
     C_air20C_pipe = 135 * (D ^ 4 / L) * p_avg + 12.1 * (D ^ 3 / L) * ((1 + 192 * D * p_avg) / (1 + 237 * D * p_avg))
End If

End Function
'=========================================================
```

And, this User Defined Function (UDF) is used as follows:



Another Ex:



One more Ex:

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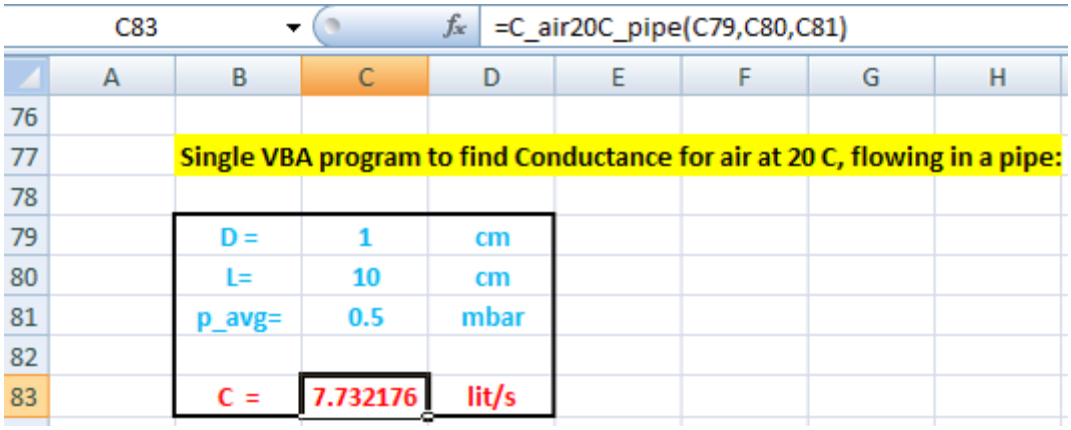

C83 =C_air20C_pipe(C79,C80,C81)

	A	B	C	D	E	F	G	H
76								
77		Single VBA program to find Conductance for air at 20 C, flowing in a pipe:						
78								
79		D =	1	cm				
80		L=	10	cm				
81		p_avg=	0.5	mbar				
82								
83		C =	7.732176	lit/s				

7.4.2 MATHCAD PROGRAMS:

Ref for equations: Leybolds Fundamentals:

A single Mathcad Function is written to give Conductances (lit/s) for air at 20 C, flowing in a pipe of dia D (cm) and length L (cm), for all the three flow regimes, viz. Laminar, Molecular and Transition flow.

$$\text{Conductance\_air20C}(D,L,p\_avg) := \left| \begin{array}{l} C \leftarrow 135\cdot\frac{D^4}{L}\cdot p\_avg \quad \text{if } p\_avg\cdot D \geq 0.6 \\ C \leftarrow 12.1\cdot\frac{D^3}{L} \quad \text{if } p\_avg\cdot D \leq 0.01 \\ C \leftarrow 135\cdot\frac{D^4}{L}\cdot p\_avg + 12.1\cdot\frac{D^3}{L}\cdot\frac{1+192\cdot D\cdot p\_avg}{1+237\cdot D\cdot p\_avg} \quad \text{if } 0.01<p\_avg\cdot D<0.6 \\ A \leftarrow \text{"Laminar"} \quad \text{if } (p\_avg\cdot D \geq 0.6) \\ A \leftarrow \text{"Molecular"} \quad \text{if } p\_avg\cdot D \leq 0.01 \\ A \leftarrow \text{"Transition"} \quad \text{if } 0.01<p\_avg\cdot D<0.6 \\ \begin{bmatrix} \text{"C (lit/s)"} & \text{"p\_avg*D (mbar.cm)"} & \text{"Type of flow"} \\ C & p\_avg\cdot D & A \end{bmatrix} \end{array} \right.$$

Examples:

Ex. 1:

$D := 1$ cm $L := 10$ cm $p\_avg := 5$ mbar

$$\text{Conductance\_air20C}(D,L,p\_avg) = \begin{bmatrix} \text{"C (lit/s)"} & \text{"p\_avg*D (mbar.cm)"} & \text{"Type of flow"} \\ 67.5 & 5 & \text{"Laminar"} \end{bmatrix}$$

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Ex. 2:

$D := 1 \quad cm \qquad L := 10 \quad cm \qquad p\_avg := 0.5 \quad mbar$

$$Conductance\_air20C(D, L, p\_avg) = \begin{bmatrix} \text{"C (lit/s)"} & \text{"p\_avg*D (mbar.cm)"} & \text{"Type of flow"} \\ 7.732 & 0.5 & \text{"Transition"} \end{bmatrix}$$

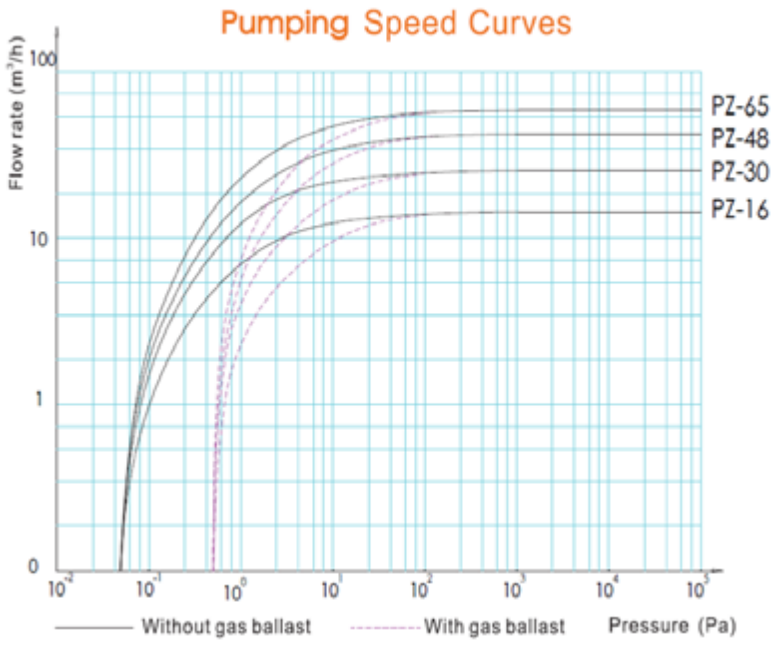
Ex. 3:

$D := 1 \quad cm \qquad L := 10 \quad cm \qquad p\_avg := 0.005 \quad mbar$

$$Conductance\_air20C(D, L, p\_avg) = \begin{bmatrix} \text{"C (lit/s)"} & \text{"p\_avg*D (mbar.cm)"} & \text{"Type of flow"} \\ 1.21 & 5 \cdot 10^{-3} & \text{"Molecular"} \end{bmatrix}$$

7.5 EVACUATION TIME FOR VACUUM SYSTEMS

A. Calculating evacuation time for small, laboratory scale volumes using a Rotary vane or piston pump is rather easy. In the working pressure range of these pumps, the pumping speed is relatively constant (see graphs below:); also the conductance of pipe is independent of pressure in molecular flow region.



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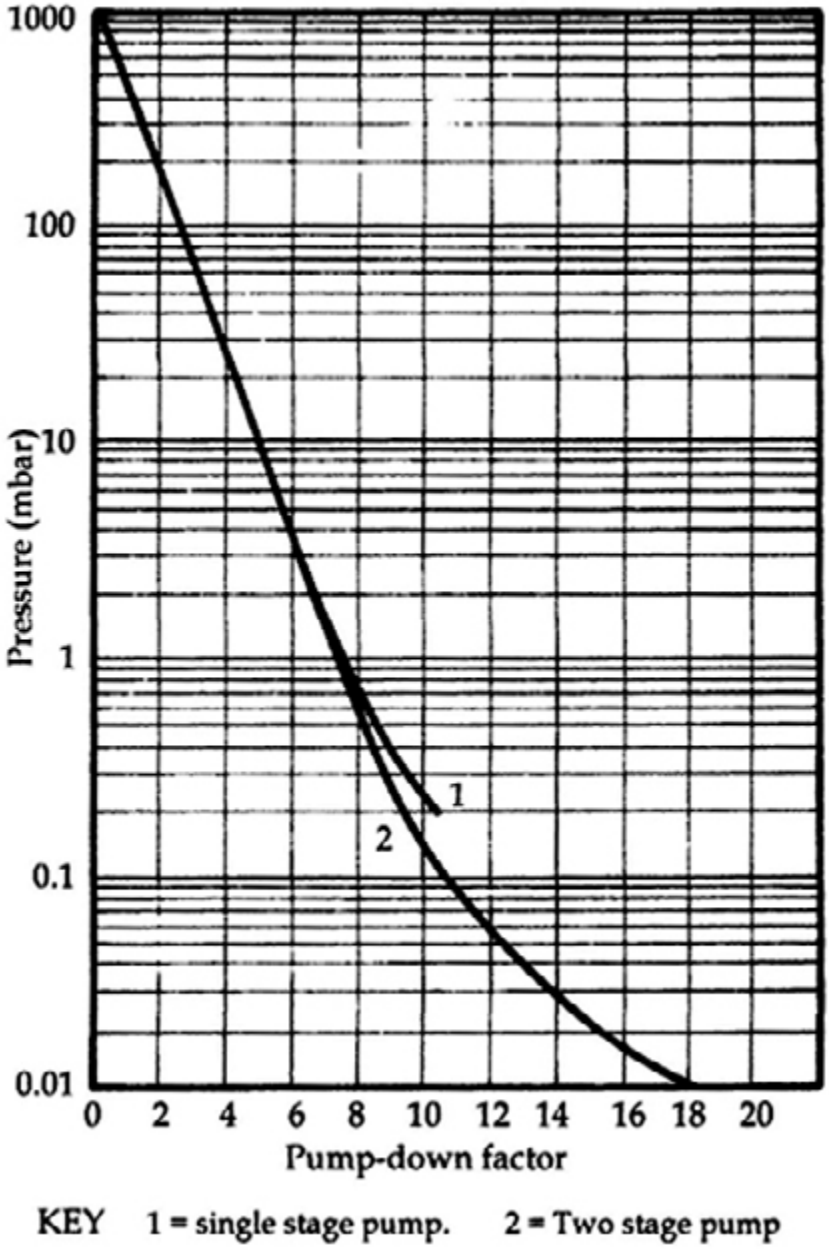
For a quick estimate of evacuation time of a Rotary pump system (i.e. rough/medium vacuum system), following method may be used:

Ref: https://vacaero.com/information-resources/vacuum-pump-technology-education-and-training/993-calculating-evacuation-time.html



Note: 1 kPa = 10 mbar. = 7.5 torr = 7.5 * 10^3 microns.

The simple formula used for this calculation is: **T = (V / S) * F**

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Here, T is time, V is volume, S is pumping speed and F is a pump down factor taken from the graph shown above. The units used should be consistent, i.e. Time in minutes, Volume in cubic feet and Speed in cubic feet per minute (cfm). Or, use liters for Volume, and liters per minute for Speed.

This formula assumes a clean, open, vacuum chamber and short connections to the pump.

As an example, if we have to pump a volume of 1.25 m^3 from atmospheric pressure (i.e. 101.3 kPa) to 1.5 kPa with a Rotary pump of pumping speed 720 lit/min, what is the time required?

We have:

V = 1250 lit, Sp = 720 lit/min., p = 1.5 kPa = 15 mbar

Then, from the graph above, for p = 15 mbar, F = 5 (approx.)

Then, evacuation time = (V/Sp) * F = 8.7 min.

Alternatively:

Instead of referring to the graph, we have digitized it and then did a curve fit and the equations are as follows:

For single stage Rotary pump:

From 1000 mbar to 10 mbar:

F = -1.0544 * ln(P) … remember: P is in mbar

From <10 mbar to 0.2 mbar:

$F = 7.7035 * P^{-0.1753}$

For two stage Rotary pump:

From 1000 mbar to 10 mbar:

F = -1.0544 * ln(P) … remember: P is in mbar

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From <10 mbar to 0.2 mbar:

$F = -1.066 * \ln(P) + 7.4257$

From <0.2 mbar to 0.01 mbar:

$F = 6.28985 * P^{-0.22353}$

Using the above Formulas in Excel, let us work out another problem:

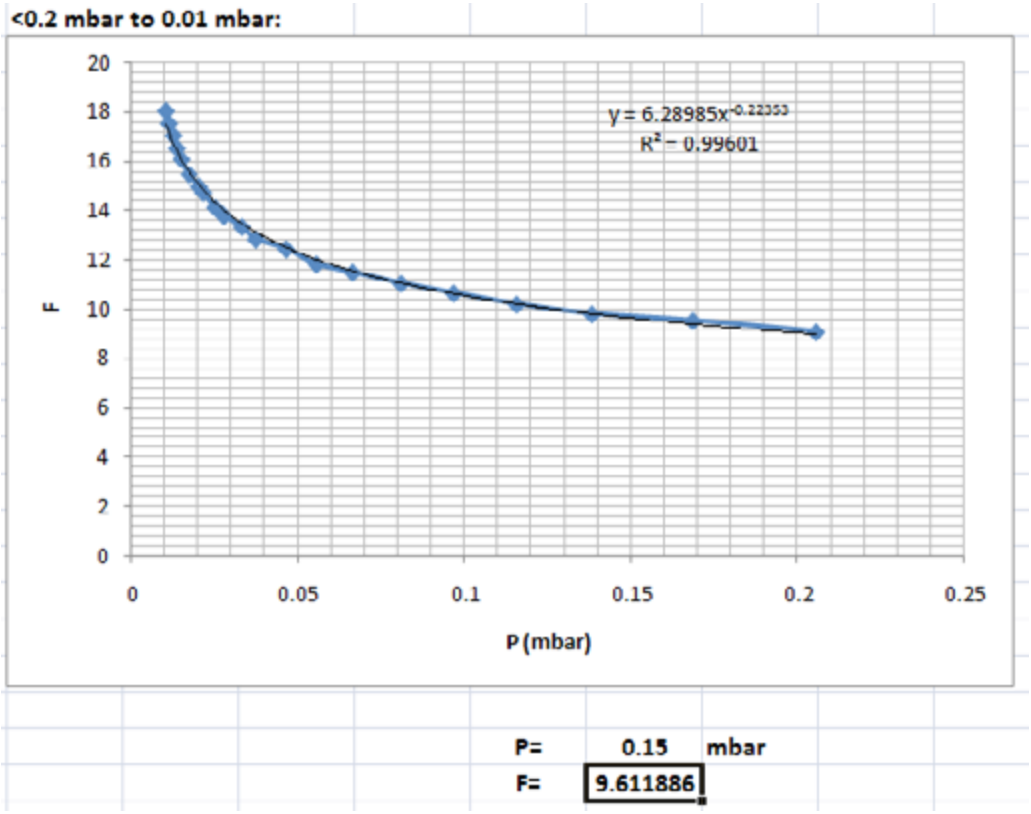
If we have to pump a volume of 1.25 m^3 from atmospheric pressure (i.e. 1000 mbar) to 0.15 mbar with a Rotary pump of pumping speed 720 lit/min, what is the time required?

We have:

V = 1250 lit, Sp = 720 lit/min., p = 0.15 mbar

Then, from the Excel worksheet shown below:

for p = 0.15 mbar, we get : F = 9.61 (approx.)



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Then, evacuation time = (V/Sp) * F = 16.68 min.

Using Mathcad Functions:

Function to find Pump down time with 1 stage RVP .

Pump down up to P_f = 0.2 mbar:

$$\text{Pumpdown\_time\_RVP1}(P\_f, V, S) := \left| \begin{array}{l} \text{return "P\_f must be >=0.2 mbar" if } P\_f < 0.2 \\ F \leftarrow -1.0544 \cdot \ln(P\_f) + 7.6350 \text{ if } P\_f \geq 10 \\ F \leftarrow 7.7035 \cdot P\_f^{0.1753} \text{ if } P\_f < 10 \\ t \leftarrow \left(\frac{V}{S}\right) \cdot F \\ \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min"} & \text{"Factor F"} & \text{"time (min)"} \\ V & S & F & t \end{bmatrix} \end{array} \right.$$

Ex:

$P\_f := 0.2 \qquad V := 100 \qquad S := 400$

$AAA := \text{Pumpdown\_time\_RVP1}(P\_f, V, S)$

$$AAA = \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min"} & \text{"Factor F"} & \text{"time (min)"} \\ 100 & 400 & 10.21451 & 2.55363 \end{bmatrix}$$

Function to find Pump down time with 2 stage RVP ..

Pump down up to P_f = 0.01 mbar:

$$\text{Pumpdown\_time\_RVP2}(P\_f, V, S) := \left| \begin{array}{l} \text{return "P\_f must be >= 0.01" if } P\_f < 0.01 \\ F \leftarrow -1.0544 \cdot \ln(P\_f) + 7.6350 \text{ if } P\_f \geq 10 \\ F \leftarrow -1.0660 \cdot \ln(P\_f) + 7.4257 \text{ if } (P\_f < 10) \cdot (P\_f \geq 0.2) \\ F \leftarrow 6.28985 \cdot P\_f^{0.22353} \text{ if } (P\_f < 0.2) \cdot (P\_f \geq 0.01) \\ t \leftarrow \left(\frac{V}{S}\right) \cdot F \\ \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"Factor F"} & \text{"time (min)"} \\ V & S & F & t \end{bmatrix} \end{array} \right.$$

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Ex:

$P\_f := 0.2 \quad V := 100 \quad S := 400$

$YY := Pumpdown\_time\_RVP2(P\_f, V, S)$

$$YY = \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"Factor F"} & \text{"time (min)"} \\ 100 & 400 & 9.14136 & 2.28534 \end{bmatrix}$$

Function to find Pump down time with RVP (both 1 stage and 2 stage) ..

Pump down up to P_f = 0.2 mbar or 0.01 mbar:

$$Pumpdown\_time\_RVP(P\_f, V, S) := \left| \begin{array}{l} \text{return "P should be >= 0.01 bar" if } P\_f < 0.01 \\ t \leftarrow Pumpdown\_time\_RVP1(P\_f, V, S)_{1,3} \text{ if } (P\_f \geq 0.2) \\ F \leftarrow Pumpdown\_time\_RVP1(P\_f, V, S)_{1,2} \text{ if } (P\_f \geq 0.2) \\ t \leftarrow Pumpdown\_time\_RVP2(P\_f, V, S)_{1,3} \text{ if } (P\_f < 0.2)\ (P\_f \geq 0.01) \\ F \leftarrow Pumpdown\_time\_RVP2(P\_f, V, S)_{1,2} \text{ if } (P\_f < 0.2) \cdot (P\_f \geq 0.01) \\ \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"P\_f (mbar)"} & \text{"Factor F"} & \text{"time (min)"} \\ V & S & P\_f & F & t \end{bmatrix} \end{array} \right.$$

Ex:

$P\_f := 0.15 \quad V := 1250 \quad S := 720 \quad lit/min$

$AY := Pumpdown\_time\_RVP(P\_f, V, S)$

$$AY = \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"P\_f (mbar)"} & \text{"Factor F"} & \text{"time (min)"} \\ 1.25 \cdot 10^3 & 720 & 0.15 & 9.61189 & 16.6873 \end{bmatrix}$$

==========

Another method **of calculation of pump down time from atmospheric pressure up to a final pressure, Pf= 1 Pa (= 7.5 microns) is using system allowance factors for different pressure ranges as follows.** ***This method is simpler*** **than the methods described above:**

We have:

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Pr. range (Pa)	Fs
10 ^5 - 10^4	1
!0^4 -- 10^3	1.25
10^3 ---10^2	1.5
10^2 ---10	2
10 - 1	4

Now, write a Mathcad Function to find the pump down time from atm to 1 Pa:

Pumpdown_time_to_1Pa(P_f, V, S) :=

return "P_f should be .= 1 Pa" if P_f<1

if $P\_f \geq 10^4$

$Fs \leftarrow 1$

$t \leftarrow \ln\left(\frac{100000}{P\_f}\right) \cdot \frac{Fs \cdot V}{S}$

if $(P\_f < 10^4) \cdot (P\_f \geq 10^3)$

$Fs \leftarrow 1.25$

$t \leftarrow \ln(10) \cdot \frac{V}{S} + \ln\left(\frac{10000}{P\_f}\right) \cdot \frac{Fs \cdot V}{S}$

if $(P\_f < 10^3) \cdot (P\_f \geq 10^2)$

$Fs \leftarrow 1.5$

$t \leftarrow \ln(10) \cdot \frac{V}{S} + \ln(10) \cdot \frac{1.25 \cdot V}{S} + \ln\left(\frac{1000}{P\_f}\right) \cdot \frac{Fs \cdot V}{S}$

if $(P\_f < 10^2) \cdot (P\_f \geq 10)$

$Fs \leftarrow 2$

$t \leftarrow \ln(10) \cdot \frac{V}{S} + \ln(10) \cdot \frac{1.25 \cdot V}{S} + \ln(10) \cdot \frac{1.5 \cdot V}{S} + \ln\left(\frac{100}{P\_f}\right) \cdot \frac{Fs \cdot V}{S}$

if $(P\_f < 10) \cdot (P\_f \geq 1)$

$Fs \leftarrow 4$

$t \leftarrow \ln(10) \cdot \frac{V}{S} + \ln(10) \cdot \frac{1.25 \cdot V}{S} + \ln(10) \cdot \frac{1.5 \cdot V}{S} + \ln(10) \cdot \frac{2 \cdot V}{S} + \ln\left(\frac{10}{P\_f}\right) \cdot \frac{Fs \cdot V}{S}$

"V (lit)"	"S (lit/min)"	"P_f (Pa)"	"Time (min)"
V	S	P_f	t

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Ex:

$P\_f := 10$ Pa $V := 10^4$ lit $S := 9000$ lit/min

BY := Pumpdown_time_to_1Pa(P_f, V, S)

$$BY = \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"P_f (Pa)"} & \text{"Time (min)"} \\ 1 \cdot 10^4 & 9 \cdot 10^3 & 10 & 14.71096 \end{bmatrix}$$

==========

To find out pump down time from an initial pressure, P1 (Pa) to final pressure P2 (Pa):

We modify the Function written above:

Pumpdown_time_P1_to_P2(P1, P2, V, S) :=

return "P2 should be >.= 1 Pa" if P2<1

return "P1 should be <.= 10^5 Pa" if $P1>10^5$

t← $\text{Pumpdown\_time\_to\_1Pa}(P2, V, S)_{1,3}$ if $P1=10^5$

if $P1<10^5$

  t2← $\text{Pumpdown\_time\_to\_1Pa}(P2, V, S)_{1,3}$

  t1← $\text{Pumpdown\_time\_to\_1Pa}(P1, V, S)_{1,3}$

  t← t2 – t1

"V (lit)"	"S (lit/min)"	"P1 (Pa)"	"P2 (Pa)"	"Time (min)"
V	S	P1	P2	t

In the above program, we find the pump down time from P1 to P2 as the difference between the pump down times required from atm to P2 and from atm to P1.

As an example:

Ex:

P1 := 200 Pa P2 := 10 Pa

$V := 10^4$ lit S := 9000 lit/min

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XY := Pumpdown_time_P1_to_P2(P1, P2, V, S)

$$XY = \begin{bmatrix} \text{"V (lit)"} & \text{"S (lit/min)"} & \text{"P1 (Pa)"} & \text{"P2 (Pa)"} & \text{"Time (min)"} \\ 1 \cdot 10^4 & 9 \cdot 10^3 & 200 & 10 & 6.2721 \end{bmatrix}$$

==========

Thus, the pump down time from P1 = 200 Pa to P2 = 10 Pa is 6.27 min.

"----------"

Now, write a corresponding Excel VBA program to find the pump down time from atm to 1 Pa:

We have:

Pr. range (Pa)	Fs
10 ^5 - 10^4	1
!0^4 -- 10^3	1.25
10^3 ---10^2	1.5
10^2 ---10	2
10 - 1	4

We have the VBA program:

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```
Function Pumpdown_time_to_1Pa(V As Double, S As Double, P_f As Double) As Variant

'Gives the Pump down time (min) with  Rotary Vacuum Pump (RVP), for air at 20 C, starting from atm (100000 Pa)
'up to a final pressure P_f (Pa), for a Volume V (lit), with effective pumping speed S (lit/min) of the RVP
'Note: Final pressure P_f should not be less than 1 Pa

'Author: M. Thirumaleshwar, January, 2020

Dim Fs As Double

If P_f < 1 Then

  MsgBox ("P_f must be >=1 Pa !!")

  End

End If

If (P_f >= 10 ^ 4) And (P_f < 10 ^ 5) Then

     Fs = 1

     Pumpdown_time_to_1Pa = Log(10 ^ 5 / P_f) * (V / S) * Fs

End If

If ((P_f >= 1000) And (P_f < 10 ^ 4)) Then

     Fs = 1.25

     Pumpdown_time_to_1Pa = Log(10) * (V / S) + Log(10 ^ 4 / P_f) * (V / S) * Fs

End If


If ((P_f < 1000) And (P_f >= 100)) Then

      Fs = 1.5

      Pumpdown_time_to_1Pa = Log(10) * (V / S) + Log(10) * (V / S) * 1.25 + Log(1000 / P_f) * (V / S) * Fs

End If

If ((P_f < 100) And (P_f >= 10)) Then

      Fs = 2

      Pumpdown_time_to_1Pa = Log(10) * (V / S) + Log(10) * (V / S) * 1.25 + Log(10) * (V / S) * 1.5 + _
                             Log(100 / P_f) * (V / S) * Fs

End If

If ((P_f < 10) And (P_f >= 1)) Then

      Fs = 4

      Pumpdown_time_to_1Pa = Log(10) * (V / S) + Log(10) * (V / S) * 1.25 + Log(10) * (V / S) * 1.5 + _
                             Log(10) * (V / S) * 2 + Log(10 / P_f) * (V / S) * Fs


End If

End Function
```

Also, write a VBA program to find effective pumping speed, Seff (lit/min) when required pump down time, t (min) to pump down from ambient to 1 Pa is given:

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```
Function S_eff_for_Pumpdown_to_1Pa(V As Double, t As Double, P_f As Double) As Double

 'Gives the S_eff (lit/min)of RVP for Pump down time, t (min), for air at 20 C, starting from atm (100000 Pa)
 'up to a final pressure P_f (Pa), for a Volume V (lit)
 'Note: Final pressure P_f should not be less than 1 Pa

 'Author: M. Thirumaleshwar, January, 2020


 Dim Fs As Double


 If P_f < 1 Then

   MsgBox ("P_f must be >=1 Pa !!")

   End

 End If


 If (P_f >= 10 ^ 4) And (P_f < 10 ^ 5) Then

      Fs = 1

      S_eff_for_Pumpdown_to_1Pa = Log(10 ^ 5 / P_f) * (V / t) * Fs

 End If



If ((P_f >= 1000) And (P_f < 10 ^ 4)) Then

     Fs = 1.25

     S_eff_for_Pumpdown_to_1Pa = Log(10) * (V / t) + Log(10 ^ 4 / P_f) * (V / t) * Fs

End If

If ((P_f < 1000) And (P_f >= 100)) Then

     Fs = 1.5

     S_eff_for_Pumpdown_to_1Pa = Log(10) * (V / t) + Log(10) * (V / t) * 1.25 + Log(1000 / P_f) * (V / t) * Fs


End If

If ((P_f < 100) And (P_f >= 10)) Then

     Fs = 2

     S_eff_for_Pumpdown_to_1Pa = Log(10) * (V / t) + Log(10) * (V / t) * 1.25 + Log(10) * (V / t) * 1.5 + _
                                 Log(100 / P_f) * (V / t) * Fs

End If

If ((P_f < 10) And (P_f >= 1)) Then

     Fs = 4

     S_eff_for_Pumpdown_to_1Pa = Log(10) * (V / t) + Log(10) * (V / t) * 1.25 + Log(10) * (V / t) * 1.5 + _
                               Log(10) * (V / t) * 2 + Log(10 / P_f) * (V / t) * Fs


End If


End Function
```

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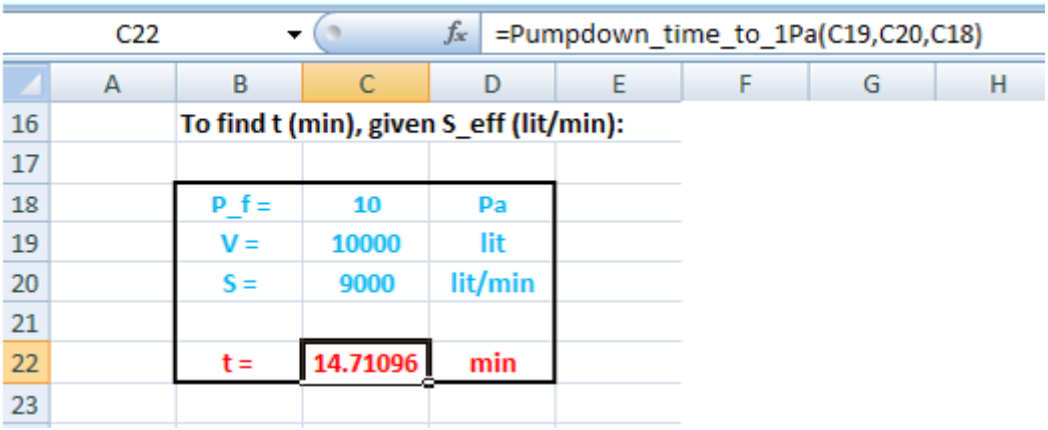
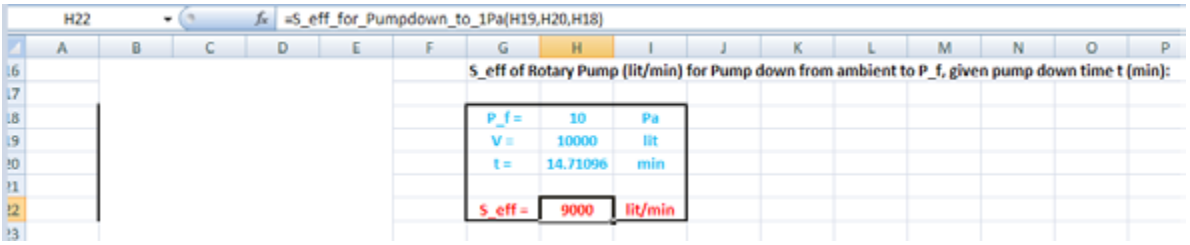
Now, use the above two User Defined Functions in Excel in the following examples:



And,


H22
=S_eff_for_Pumpdown_to_1Pa(H19,H20,H18)
S_eff of Rotary Pump (lit/min) for Pump down from ambient to P_f, given pump down time t (min):
P_f = 10 Pa
V = 10000 lit
t = 14.71096 min
S_eff = 9000 lit/min

To find out pump down time from an initial pressure, P1 (Pa) to final pressure P2 (Pa):

We modify the VBA program written above:

```
Function Pumpdown_time_P1_to_P2(P1 As Double, P2 As Double, V As Double, S As Double) As Double

'Gives the Pump down time (min) with  Rotary Vacuum Pump (RVP), for air at 20 C, starting from P1 (Pa)
'up to a final pressure P2 (Pa), for a Volume V (lit), with effective pumping speed S (lit/min) of the RVP
'Note: Final pressure P2 should not be less than 1 Pa

Dim Fs As Double, t1 As Double, t2 As Double

If P2 < 1 Then

  MsgBox ("P2 must be >=1 Pa !!")

  End

End If

If P1 > 10 ^ 5 Then

  MsgBox ("P1 must be <=10^5 Pa !!")

  End

End If
```

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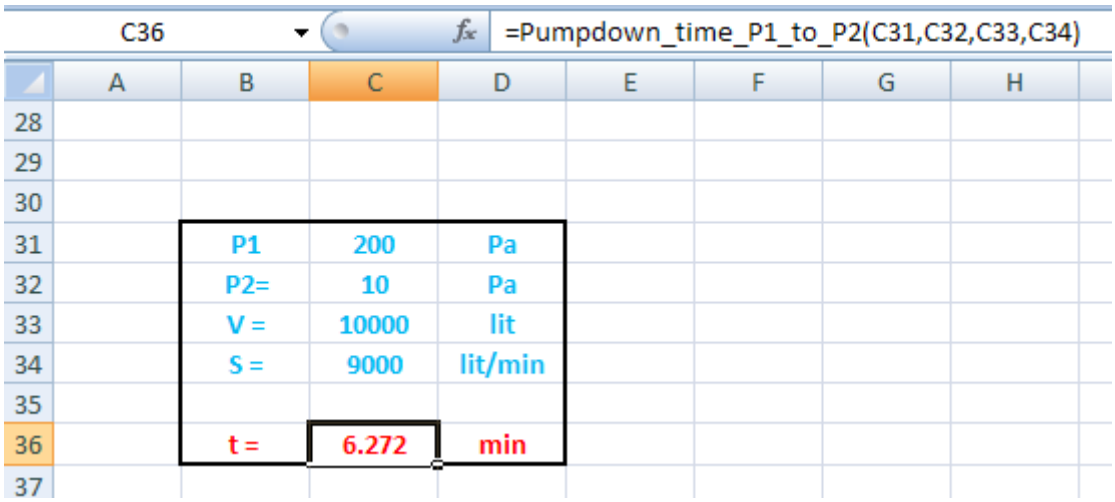
```
 If P1 = 10 ^ 5 Then

   Pumpdown_time_P1_to_P2 = Pumpdown_time_to_1Pa(V, S, P2)

 End If

If P1 < 10 ^ 5 Then

   t2 = Pumpdown_time_to_1Pa(V, S, P2)

   t1 = Pumpdown_time_to_1Pa(V, S, P1)

   Pumpdown_time_P1_to_P2 = t2 - t1

End If


End Function
```

An example of the use of above code:



B. Evacuation of larger volumes with Roots pump, backed by a Rotary pump:

Ref:

https://vacaero.com/information-resources/vacuum-pump-technology-education-and-training/993-calculating-evacuation-time.html

This method is useful for evacuation of large volumes. Roots pump has a very high pumping speed around the vacuum level where water vapor evolves from the system surfaces and it also reduces the chamber pressure by about one decade.

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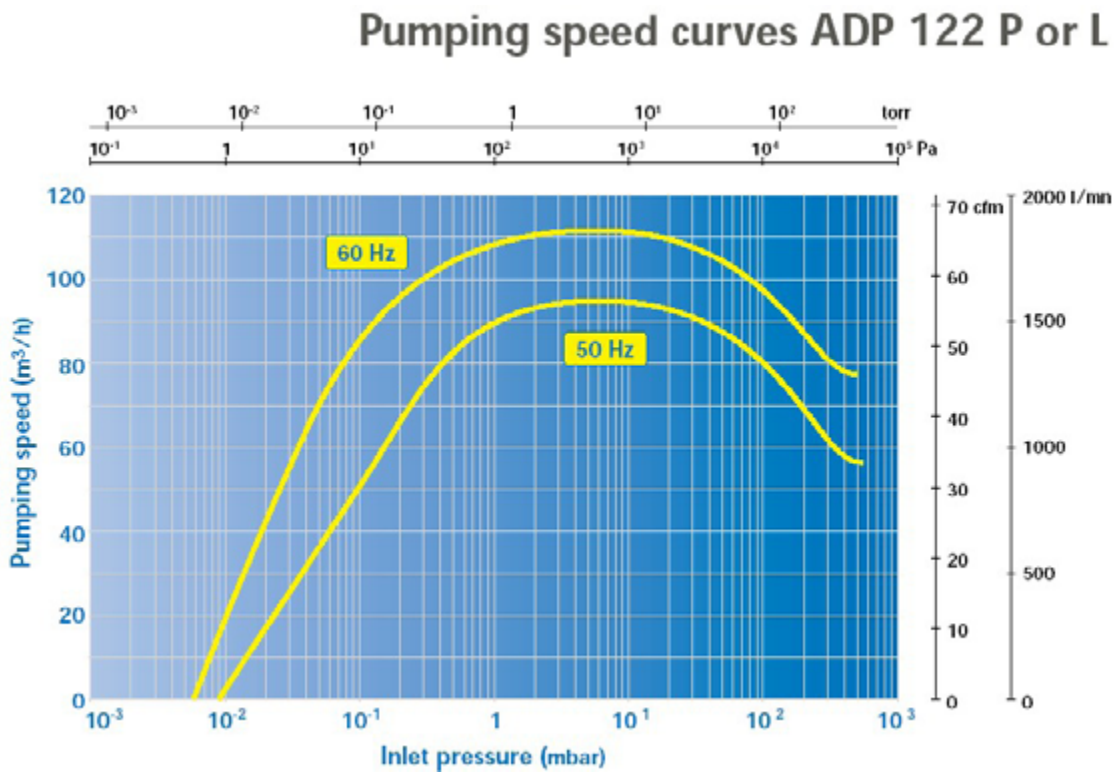
A combination of the two-pump designs works well because the Roots booster has a very high pumping speed and the mechanical oil-sealed pump has a high compression ratio.

The pumping speed against pressure graph for a vacuum booster pump is not a smooth curve.

See below:



The pump speed curve is a 'bell-shaped' curve and rises to a peak from startup and then drops off as the pressure drops. Because of this variation, we calculate the pump-down time in segments, by dividing the pressure range from atmospheric to desired pressure of, say 0.01 mbar, as: 1000 to 100 mbar, 100 to 10 mbar, 10 to 5 mbar, 5 to 1 mbar, 1 to 0.1 mbar, and 0.1 to 0.01 mbar. And, it is easy to calculate this in EXCEL.

We show an example below:

Volume, V = 196 lit, Pipe dia, D = 4 cm, pipe length, L = 300 cm

Calculate the time required to pump down to 0.01 mbar.

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The procedure is as follows:

1. First, consider the lower curve (for 50 Hz) in the pumping speed curves shown above. Digitize it using a digitization software such as GetData Graph digitizer.
2. Transfer the digitized data to Excel

In Excel, first, **create a User Defined Function "Linear_ Interp(x, x_values,y_values),** by writing a VBA code for Linear Interpolation at any given x, when the x_values and y_values are Input:

```
Option Explicit

Function Linear_Interp(x As Double, xvalues As Range, yvalues As Range) As Variant

'Based on Ref: Charlie Young, P.E., engineerexcel.com

Dim x1 As Double, y1 As Double, x2 As Double, y2 As Double

'xvalues must be ascending from top to bottom

x1 = Application.WorksheetFunction.Index(xvalues, Application.WorksheetFunction.Match(x, xvalues, 1))

x2 = Application.WorksheetFunction.Index(xvalues, Application.WorksheetFunction.Match(x, xvalues, 1) + 1)

y1 = Application.WorksheetFunction.Index(yvalues, Application.WorksheetFunction.Match(x, xvalues, 1))

y2 = Application.WorksheetFunction.Index(yvalues, Application.WorksheetFunction.Match(x, xvalues, 1) + 1)

Linear_Interp = y1 + (y2 - y1) * (x - x1) / (x2 - x1)

End Function
```

This code is based on a very useful VBA code by Charlie Young of Engineerexcel.com

Ref: https://www.engineerexcel.com/linear-interpolation-vba-function-in-excel/

3. Now, using the above written Function, one can get the pumping speed at any pressure in the range of digitized data.

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4. Remember that the x axis for Pressure (mba) is in log scale. So, *one should be careful in applying Linear Interpolation*. Therefore, have a large number of closely spaced data, to reduce the error.
5. Now, divide the pressure range from starting pressure (1000 mbar) to the final pressure (0.01 mbar) in to a few intervals and build up the Excel Table shown below:

	Vol(lit)	D_pipe (cm)	L_pipe(cm)	visc, air, 20C (poise)
	196	4	300	1.71E-04

Increment No.	P (mbar)	P_av(mbar)	C_visc (lit/s)	C_mol(lit/s)	C_ap_visc	C_tube(lit/s)	C_tot(lit/s)	S_interp(lit/s)	Del_speed(lit/s)	Increm. Time (s)	Elapsed time (s)
	1000										0
1	500	750	86400	2.58	251.33	86402.58	250.60	15.70	14.78	9.19	9.19
2	100	300	34560	2.58	251.33	34562.58	249.51	17.26	16.14	19.55	28.74
3	10	55	6336	2.58	251.33	6338.58	241.74	24.12	21.93	20.58	49.31
4	5	7.5	864	2.58	251.33	866.58	194.82	26.45	23.29	5.83	55.15
5	1	3	345.6	2.58	251.33	348.18	145.97	26.22	22.23	14.19	69.34
6	0.5	0.75	86.4	2.58	251.33	88.98	65.72	24.21	17.69	7.68	77.02
7	0.1	0.3	34.56	2.58	251.33	37.14	32.36	20.61	12.59	25.05	102.07
8	0.01	0.055	6.336	2.58	251.33	8.92	8.61	10.60	4.75	94.97	197.04

For clarity, we show the above Table in two halves:

	B	C	D	E	F	G	H
		Vol(lit)	D_pipe (cm)	L_pipe(cm)	visc, air, 20C (poise)		
		196	4	300	1.71E-04		
	Increment No.	P (mbar)	P_av(mbar)	C_visc (lit/s)	C_mol(lit/s)	C_ap_visc	C_tube(lit/s)
		1000					
	1	500	750	86400	2.58	251.33	86402.58
	2	100	300	34560	2.58	251.33	34562.58
	3	10	55	6336	2.58	251.33	6338.58
	4	5	7.5	864	2.58	251.33	866.58
	5	1	3	345.6	2.58	251.33	348.18
	6	0.5	0.75	86.4	2.58	251.33	88.98
	7	0.1	0.3	34.56	2.58	251.33	37.14
	8	0.01	0.055	6.336	2.58	251.33	8.92

I	J	K	L	M
C_tot(lit/s)	S_interp(lit/s)	Del_speed(lit/s)	Increm. Time (s)	Elapsed time (s)
				0
250.60	15.70	14.78	9.19	9.19
249.51	17.26	16.14	19.55	28.74
241.74	24.12	21.93	20.58	49.31
194.82	26.45	23.29	5.83	55.15
145.97	26.22	22.23	14.19	69.34
65.72	24.21	17.69	7.68	77.02
32.36	20.61	12.59	25.05	102.07
8.61	10.60	4.75	94.97	197.04

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6. Volume to be evacuated (lit), Dia (cm) and Length (cm) of pipe are shown on the top of the Table.
7. There are 12 columns and note the headings of columns.
8. Let the starting pressure be P1 = 1000 mbar, and the final pressure of first increment be P2 = 500 mbar. Then, calculations for other columns are described below:
9. P_av = (P1 + P2)/2. = 750 mbar
10. Viscous flow Conductance, for air at 20 C: C_visc = 1.35 * D^4 * p_av /L ,(lit/s), remember: D, L in cm, p_av in Pa. C_visc = 86400 lit/s
11. Mol flow Conductance, for air at 20 C: We get C_mol = 12.1 * D^3 /L (lit/s), remember: D, L in cm. We get C_mol = 2.58 it/s
12. Viscous Conductance of aperture for air at 20 C: C_ap_visc = 20 * π * D^2 / 4, lit/s, where D is in cm. We get C_ap_visc = 251.33 lit/s
13. Then, tube conductance of tube, C_tube = C_visc + C_mol. We get C_tube = 86402.58 lit/s
14. And, overall conductance at the chamber, including the aperture is: C_tot = 1 / { 1/C_tube + 1/C_ap_visc}. We get: C_tot = 250.6 lit/s
15. And, find the interpolated value of pumping speed from the curve with Linear_ Interp function in Excel. It is shown under S_interp, in lit/s. We get S_interp = 15.7 lit/s at p_av = 750 mbar
16. Then, the delivered speed at the chamber is easily calculated as:
    Del_speed = (S_interp * C_tot) / (S_interp + C_tot), lit/s. We get Del_speed = 14.78 lit/s
17. Now, the incremental time for evacuation for the first increment (from 1000 mbar to 500 mbar) is calculated as:
    Increm. Time = (V / Del_speed) * ln(P1/P2) = (196 /14.78) * ln(1000/500) = 9.19 s
18. And, the elapsed time for the first increment is 9.19 s itself.
19. And, repeat the calculations for the next increment of P1 = 500 mar, P2 = 100 mbar, and we get increm. Time for this increment as 19.55 s, and the elapsed time is 9.19 + 19.55 = 28.74 s.
20. Thus, repeating for all the increments, we get: the total elapsed time = 197.04 s. = pump down time.

Note: If we divide the pressure range of 1000 mar – 0.01 mbar in to more sub-divisions, we will get more accurate results, and the pump down time will be slightly different from 197.04 sec.

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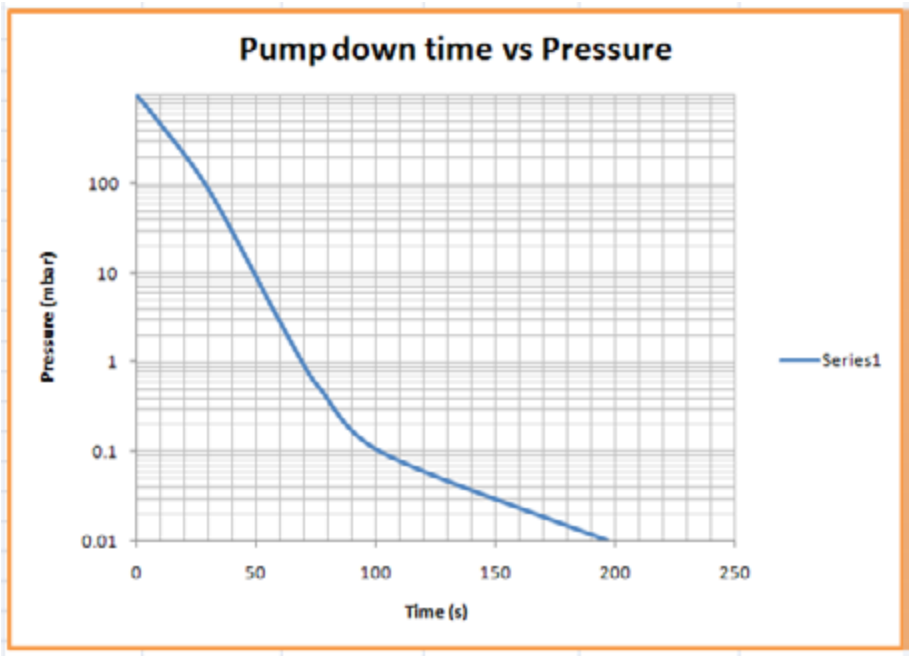
Now, we plot the pump down curve:

We have the Table:

Elapsed time (s)	P (mbar)
0	1000
9.19	500
28.74	100
49.31	10
55.15	5
69.34	1
77.02	0.5
102.07	0.1
197.04	0.01

And, plot, in EXCEL:



Solution with Mathcad:

1. First, consider the lower curve (for 50 Hz) in the pumping speed curves shown above. Digitize it using a digitization software such as GetData Graph digitizer.
2. Transfer the digitized data to Mathcad as a matrix, M_ADP122L, as shown below, only partially, to save space:

M_ADP122L:=

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P(mbar)	S(m^3/h)
0.009284736	0.573796166
0.011612474	4.825882679
0.013480402	7.749102948
0.014526177	9.874432528
0.016449507	12.53168923
0.017724647	14.39153104
0.019099681	16.51686061
0.02162264	17.84667843
0.023300069	19.97200801
0.025737031	22.09781337
0.027050971	23.42620383
0.0298/8604	25.28652142
0.033829103	27.14731479
0.036457474	29.80361993
0.040266161	31.39844974

“----------“

“----------“

123.8559166	77.21650179
133.3766463	76.15597803
154.6868667	74.56590607
158.5211547	73.23894297
170.7065804	72.17841921
183.8186232	70.85240767
207.9746622	69.26185992
235.2922144	67.4058244
241.1112933	65.81337351
259.6453732	64.75284975
279.5888413	63.42683821
308.5774834	61.5703269
340.5904142	59.97930337
375.9450733	58.65376762
394.986526	58.12374363
436.0832593	57.86015899
493.4710749	57.06607458
518.5219707	57.06702615
544.7848806	56.53700216

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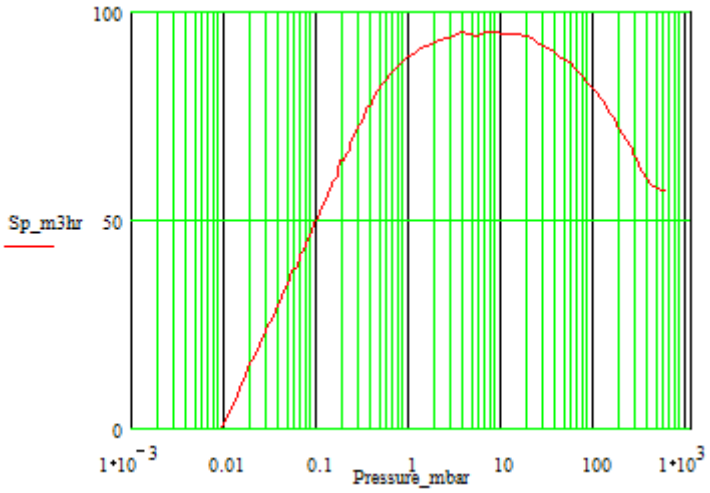
Then,

Pressure_mbar := M_ADP122L$^{<0>}$ Sp_m3hr := M_ADP122L$^{<1>}$



Note:

1m^3/hr = 0.27778 lit/s

1 Torr = 133.3227 Pa

1 mbar = 0.75006 torr = 100 Pa

Now, write a Function for pumping speed of the Roots pump, in lit/s:

PumpingSpeed_litpersec(P_mbar) := 56.537 0.27778 if (P_mbar≥544.785) (P_mbar≤1000)
⟨linterp(M_ADP122L$^{<0>}$, M_ADP122L$^{<1>}$, P_mbar)⟩ 0.27778 if (P_mbar<544.78488)

Ex

PumpingSpeed_litpersec(1000) = 15.70485 lit/s

Now, let us solve this problem:

Problem
1 meter high by 50 cm dia. Cylindrical Vessel
40 mm foreline, 10' long
Pump ADP 122 P at 60 Hz

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Estimate the pump down time to 0.01 mbar.

Chamber Volume		
height	100	
diamter	50	
Volume	196	liters

First, let us write a simple Mathcad Function to find the pump down time from P1 to P2 mbar, with the above data:

$V := 196$ lit $D := 4$ cm $L := 300$ cm

$P1 := 1000$ $P2 := 100$ mbar

$$\begin{aligned}
&\text{Evacuation_Time}(P1,P2,V,D,L) := \\
&\quad p_avg \leftarrow \frac{P1+P2}{2} \\
&\quad S_avg \leftarrow \text{PumpingSpeed_litpersec}(p_avg) \\
&\quad C_mol \leftarrow 12.1 \cdot \frac{D^3}{L} \\
&\quad C_visc \leftarrow 1.35 \cdot \frac{D^4}{L} \cdot p_avg \cdot 100 \\
&\quad C_tube \leftarrow C_mol + C_visc \\
&\quad C_aperture_visc \leftarrow 20 \cdot \frac{\pi \cdot D^2}{4} \\
&\quad C_tot \leftarrow \left(\frac{1}{C_tube} + \frac{1}{C_aperture_visc} \right)^{-1} \\
&\quad S_del \leftarrow \frac{S_avg \cdot C_tot}{S_avg + C_tot} \\
&\quad A \leftarrow \frac{P1}{P2} \\
&\quad t1 \leftarrow \ln(A) \cdot \frac{V}{S_del}
\end{aligned}$$

We get:

Ex:

$\text{Evacuation\_Time}(P1,P2,V,D,L) = 30.53959$ sec.

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Now, use this Function to calculate the pump down times for various sub-divisions of pressure:

Prob:

V := 196 lit D := 4 cm L := 300 cm

P1 := 1000 P2 := 500 P3 := 100 P4 := 10 P5 := 5 P6 := 1 mbar

P7 := 0.5 P8 := 0.1 P9 := 0.01 mbar

Pump_down_Time(P1,P2,P3,P4,P5,P6,P7,VP8,P9,D,L) :=

t1← Evacuation_Time(P1,P2,V,D,L)
t2← Evacuation_Time(P2,P3,V,D,L)
t3← Evacuation_Time(P3,P4,V,D,L)
t4← Evacuation_Time(P4,P5,V,D,L)
t5← Evacuation_Time(P5,P6,V,D,L)
t6← Evacuation_Time(P6,P7,V,D,L)
t7← Evacuation_Time(P7,P8,V,D,L)
t8← Evacuation Time(P8,P9,V,D,L)
t_tot← t1 + t2 + t3 + t4 + t5 + t6 + t7 + t8

"Pr. range >>"	"P1 P2"	"P2 P3"	"P3 P4"	"P4 P5"	"P5 P6"	"P6 P7"	"P7 P8"	"P8 P9"	"Total time(s)"
"Time (s)--->>"	t1	t2	t3	t4	t5	t6	t7	t8	t_tot

Then, we get:

Pump_down_Time(P1,P2,P3,P4,P5,P6,P7,P8,P9,D,L) =

	0	1	2	3	4	5	6	7	8	9
0	"Pr. range-->>"	"P1-P2"	"P2-P3"	"P3-P4"	"P4-P5"	"P5-P6"	"P6-P7"	"P7-P8"	"P8-P9"	"Total time(s)"
1	"Time (s)--->>"	9.19276	19.54528	20.5752	5.83389	14.19055	7.67776	25.05331	94.97375	197.0426

Therefore, total time for pump down from 1000 mbar to 0.01 mbar:

Total time = 197.043 sec... Ans.

Note that this matches the result obtained with EXCEL.

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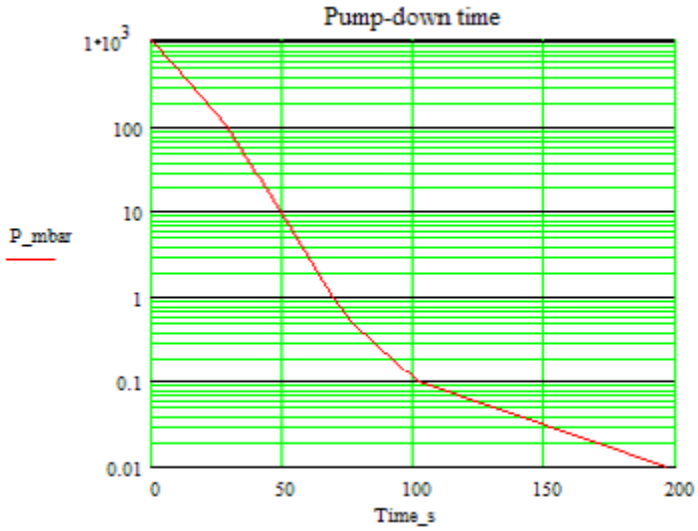
Plot the pump down curve:

	Time (s)	P (mbar)
Pump_down :=	0	1000
	9.19	500
	28.74	100
	49.32	10
	55.15	5
	69.34	1
	77.02	0.5
	102.05	0.1
	197.04	0.01

Time_s := Pump_down$^{\langle 0 \rangle}$ P_mbar := Pump_down$^{\langle 1 \rangle}$



C. Evacuation time in the high vacuum region [1]: At pressures below about 30 mPa (or, 2E-04 torr), out-gassing rate controls the pump down time.

Fundamental equation to evaluate the pump down time is:

$$\frac{dp}{dt} = \frac{Q_i}{V} - \frac{S_s \cdot p}{V}$$

Where Q_i is in-leak rate, V is the volume, S_s is system pumping speed p is the system pressure, and t is the time.

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Now, writing for Q_i and S_s, we have:

$$Q_i = Q_o \cdot \exp\left(\frac{-t}{t_1}\right)$$

$$S_s = S_o \cdot \left(1 - \frac{p_u}{p}\right)$$

where Q_o is initial out-gassing rate at t = 0, t_1 is constant characteristic of the system, S_o is the system pumping speed at pressures well above the ultimate pressure p_u of the system.

Solving, we obtain:

$$\frac{p - p_u}{p_1 - p_u} = \exp\left(\frac{-S_o \cdot t}{V}\right) + \frac{Q_o \cdot \left(\exp\left(\frac{-t}{t_1}\right) - \exp\left(\frac{-S_o \cdot t}{V}\right)\right)}{S_o \cdot (p_1 - p_u) \cdot \left[1 - \left(\frac{V}{S_o \cdot t_1}\right)\right]}$$

where p_1 is initial pressure of the system.

Out-gassing rate is expressed in terms of specific out-gassing rate per unit surface area after a certain time t_prime has elapsed, and surface area A of the system:

$$Q_i = q_1 \cdot A = Q_o \cdot \exp\left(\frac{-t\_prime}{t_1}\right)$$

Or: $$Q_o = q_1 \cdot A \cdot \exp\left(\frac{t\_prime}{t_1}\right)$$

Table 7.3 Selected values of specific outgassing rates q1: Ref. [1]

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Material	Condition	Specific Outgassing Rate, μPa-m/s	
		1 hr	10 hr
Mild steel	Shotblasted	...	80
Mild steel	...	670	67
Mild steel	As received (450°C)	560	...
Mild steel	Degreased (450°C)	480	...
Mild steel	As received (200°C)		11.5
Mild steel	As received (400°C)		11.2
Mild steel	Baked 15 hr (400°C)		0.016
Stainless steel	...	270	27
Stainless steel	Polished, degreased	...	1.9
Stainless steel	As received (450°C)	850	...
Stainless steel	Degreased (450°C)	530	...
Stainless steel	Annealed (450°C)	71	...
Stainless steel	Baked 12 hr (400°C)	...	0.0012
Aluminum	Anodized	...	130
Aluminum	As received (450°C)	1,730	...
Aluminum	As received	...	3.3
Aluminum	As received (200°C)	...	6.0
Aluminum	Baked 13.5 hr (200°C)	...	0.49
Aluminum	Baked 15 hr (300°C)	...	0.21
Copper	...	3,100	...
Copper	As received (450°C)	2,100	...
Copper	Degreased (450°C)	1,900	...
Neoprene	...	40,000	20,000
Neoprene	As received	267,000	...
Butyl rubber	...	2,000	...
Kel-F	...	53	...
Mylar	As received	4,000	...
Polyethylene	...	350	...
Nylon	...	16,000	...
Teflon	As received	6,700	...
Teflon	...	610	280
Plexiglass	Outgassed	1,330	...

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As additional information, see the following:

Typical values of specific out-gassing rates for some materials are shown in following Table **(Ref: Leybolds Fundamentals):**

At room temperature									
Standard values[1] ($mbar \cdot l \cdot s^{-1} \cdot cm^{-2}$)			Metals 10^{-9} ... $\cdot 10^{-7}$				Nonmetals 10^{-7} ... $\cdot 10^{-5}$		
Outgassing rates (standard values) as a function of time									
Examples:	1/2 hr.	1 hr.	3 hr.	5 hr.	Examples:	1/2 hr.	1 hr.	3 hr.	5 hr.
Ag	$1.5 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$2 \cdot 10^{-9}$		Silicone	$1.5 \cdot 10^{-5}$	$8 \cdot 10^{-6}$	$3.5 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$
Al	$2 \cdot 10^{-8}$	$6 \cdot 10^{-9}$			NBR	$4 \cdot 10^{-6}$	$3 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
Cu	$4 \cdot 10^{-8}$	$2 \cdot 10^{-8}$	$6 \cdot 10^{-9}$	$3.5 \cdot 10^{-9}$	Acrylic glass	$1.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-6}$	$8 \cdot 10^{-7}$	$5 \cdot 10^{-7}$
Stainless steel		$9 \cdot 10^{-8}$	$3.5 \cdot 10^{-8}$	$2.5 \cdot 10^{-8}$	FPM, FKM	$7 \cdot 10^{-7}$	$4 \cdot 10^{-7}$	$2 \cdot 10^{-7}$	$1.5 \cdot 10^{-7}$
[1] All values depend largely on pretreatment!									

Table X: Outgassing rate of materials in $mbar \cdot l \cdot s^{-1} \cdot cm^{-2}$

Example7.2. A vacuum chamber has a volume of 1.250 m^3 (44.14 ft^3), and the overall conductance of the piping between the chamber and the vacuum pump is 12 dm^3/s (25.4 ft^3/min). The initial pressure of the air within the system is 101.3 kPa (760 torr) and the temperature 11; 300 K (540°R). The ultimate pressure of the system is 0.15 mPa (1.125 x 10^{-6} torr). Determine the vacuum pump size required to pump the system to 1.50 kPa (0.01125 torr) in 1.00 hr.

Note: This is a worked out problem in Ref.[1], i.e. Barron, p 440.

Solution:

$$t_p = \left(\frac{V}{S_s}\right) \cdot \ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$$

Then, we get:

$$S_s = \left(\frac{V}{t_p}\right) \cdot \ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$$

Data:

$V := 1.25$ m^3 $t_p := 3600$ sec $p_1 := 101300$ Pa $p_2 := 1.5$ Pa

$p_u := 0.15 \cdot 10^{-3}$ Pa $C_o := 12$ lit/s.... overall conductance

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Then:

$$S_s := \left(\frac{V}{t_p}\right)\cdot\ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$$

i.e. $S_s = 3.86128\cdot10^{-3}$ m^3/s = 3.861 lit/s

Then, required pump speed is found from:

$$\frac{1}{S_p} = \frac{1}{S_s} - \frac{1}{C_o}$$

i.e. $S_p := \left(\frac{1}{3.86128} - \frac{1}{12}\right)^{-1}$ lit/s

i.e. $S_p = 5.6932$ **lit/s .... Ans.**

To be safe, choose a pump with a pumping speed of 6 or 7 lit/s

---

Write the above problem as a Function to find pump speed for pump down to medium vacuum:

$$Sp\_pumpdown\_to\_medium\_vacuum\left(V, t_p, p_1, p_2, p_u, C_o\right) := \left|\begin{array}{l} S_s \leftarrow \left(\frac{V}{t_p}\right)\cdot\ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right) \\ S_{s\_lit} \leftarrow S_s\cdot10^3 \\ S_p \leftarrow \left(\frac{1}{S_{s\_lit}} - \frac{1}{C_o}\right)^{-1} \\ \begin{bmatrix} \text{"S\_s (m^3/s)"} & \text{"S\_s(lit/s)"} & \text{"S\_p(lit/s)"} \\ S_s & S_{s\_lit} & S_p \end{bmatrix} \end{array}\right.$$

Ex:

$V := 1.25$ m^3 $t_p := 3600$ sec $p_1 := 101300$ Pa $p_2 := 1.5$ Pa

$p_u := 0.15\cdot10^{-3}$ Pa $C_o := 12$ lit/s.... overall conductance

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Using the above Function, we get:

$$\text{Sp\_pumpdown\_to\_medium\_vacuum}\left(V, t_p, p_1, p_2, p_u, C_o\right) = \begin{bmatrix} \text{"S\_s (m\^3/s)"} & \text{"S\_s(lit/s)"} & \text{"S\_p(lit/s)"} \\ 3.86128 \cdot 10^{-3} & 3.86128 & 5.69319 \end{bmatrix}$$

Another Ex: If t_p – 2500 sec, what is the pumping speed at the chamber and at the pump, other parameters remaining constant?

$t_p := 2500 \quad \text{sec}$

Then:

$$\text{Sp\_pumpdown\_to\_medium\_vacuum}\left(V, t_p, p_1, p_2, p_u, C_o\right) = \begin{bmatrix} \text{"S\_s (m\^3/s)"} & \text{"S\_s(lit/s)"} & \text{"S\_p(lit/s)"} \\ 5.56023829 \cdot 10^{-3} & 5.56023829 & 10.36107585 \end{bmatrix}$$

An EXCEL worksheet to do above calculations is shown below:

F522 =(F514/F515)*LN((F516 -F518)/(F517 - F518))

	C	D	E	F	G	H	I	J
510								
511		**Pump down of a medium vacuum system (Ref: Barron):**						
512								
513		Inputs:						
514		Volume	V	1.25	m^3			
515		Reqd pumpdown time	t_p	3600	sec			
516		Initial pressure (ambient)	p_1	101300	Pa			
517		Final pressure	p_2	1.5	Pa			
518		Ultimate pressure	p_u	1.50E-04	Pa			
519		Overall conductance between chamber and pump	C_o	12	lit/s			
520								
521		Outputs:						
522		Reqd pump speed at chamber	S_s	0.00386127659	m^3/s	←	$S_s := \left(\frac{V}{t_p}\right) \cdot \ln\left(\frac{P_1 - P_u}{P_2 - P_u}\right)$	
523		Reqd pump speed at chamber	S_s_litpersec	3.861276592	lit/s			
524		Reqd speed at the pump	S_p	5.693192505	lit/s	↳	$\frac{1}{S_p} = \frac{1}{S_s} - \frac{1}{C_o}$	
525								
526								

Formula to calculate the S_s can be seen in the Formula bar.

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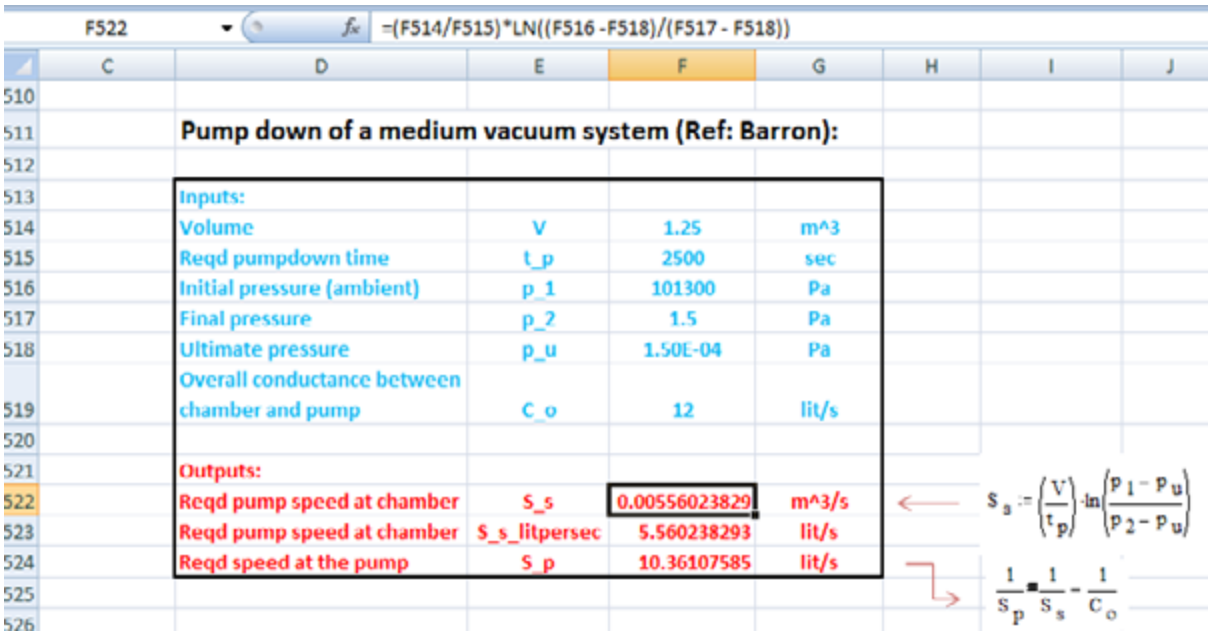
To find out what should be the required speed at the chamber (and at the pump) if the pump down time desired is 2500 sec, can be easily found by entering 2500 for t_p:


F522
=(F514/F515)*LN((F516 -F518)/(F517 - F518))
Pump down of a medium vacuum system (Ref: Barron):
Inputs:
Volume V 1.25 m^3
Reqd pumpdown time t_p 2500 sec
Initial pressure (ambient) p_1 101300 Pa
Final pressure p_2 1.5 Pa
Ultimate pressure p_u 1.50E-04 Pa
Overall conductance between chamber and pump C_o 12 lit/s
Outputs:
Reqd pump speed at chamber S_s 0.00556023829 m^3/s
Reqd pump speed at chamber S_s_litpersec 5.560238293 lit/s
Reqd speed at the pump S_p 10.36107585 lit/s

Example 7.3. A vacuum system having a volume of 1.250 m^3 (44.1 ft^3) and a surface area of 6.23 m^2 (67.1 ft^2) is initially at 1.50 Pa (0.01125 torr). The specific outgassing rate is q_1 = 2.50 x 10^{-6} Pa-m/s at t_prime = 1 hr = 3600 s. The ultimate pressure for the system is 0.015 mPa (1.125 x 10^{-7} torr). The outgassing constant t_1 = 4 hr = 14,400 s. Determine the system pumping speed required to attain a pressure of 0.150 mPa in 3 hr = 10,800 s.

Note: This is a worked out problem in Ref.[1], i.e. Barron, p 442.

Solution:

We have:

Data:

$q_1 := 2.5 \cdot 10^{-6}$ Pa-m/s t_prime := 3600 sec A := 6.23 m^2 V := 1.25 m^3

$p_u := 0.015 \cdot 10^{-3}$ Pa $t_1 := 14400$ sec....outgassing const.

$p := 0.15 \cdot 10^{-3}$ Pa .... desired pressure t := 10800 sec

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We have:

$$Q_o := q_1 \cdot A \cdot \exp\left(\frac{t\_prime}{t_1}\right)$$

i.e. $Q_o = 1.99987 \cdot 10^{-5}$ Pa-m^3/s

Then, we have:

$$\frac{p - p_u}{p_1 - p_u} = \exp\left(\frac{-S_o \cdot t}{V}\right) + \frac{Q_o \cdot \left(\exp\left(\frac{-t}{t_1}\right) - \exp\left(\frac{-S_o \cdot t}{V}\right)\right)}{S_o \cdot (p_1 - p_u) \cdot \left[1 - \left(\frac{V}{S_o \cdot t_1}\right)\right]}$$

In this low pressure range here, the term exp(-So * t /V) is negligible.

So, above eqn reduces to:

$$p - p_u = \frac{Q_o \cdot \exp\left(\frac{-t}{t_1}\right)}{S_o - \left(\frac{V}{t_1}\right)}$$

So, required pumping speed S_o is calculated:

$$S_o := \frac{V}{t_1} + \frac{Q_o \cdot \exp\left(\frac{-t}{t_1}\right)}{p - p_u}$$

i.e. $S_o = 0.07006$ **m^3/s = 70.06 lit/s .....Ans.**

Note: Check if the value of exp(-So * t /V) is nedligible, as assumed:

$$\exp\left(-S_o \cdot \frac{t}{V}\right) = 0$$ **...yes, it is negligible.**

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Important: System piping conductance must be greater than 70.06 lit/s to achieve the required pump down. This shows the importance of high conductance piping (large dia and short lengths) for high vacuum systems.

'----------

Write the above problem as a Function to find pump speed for pump down to high vacuum:

$$Sp\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, t) :=$$

$$Q_o \leftarrow q_1 \cdot A \cdot \exp\left(\frac{t\_prime}{t_1}\right)$$

$$S_o \leftarrow \frac{V}{t_1} + \frac{Q_o \cdot \exp\left(\frac{-t}{t_1}\right)}{p - p_u}$$

$$check \leftarrow \exp\left(-S_o \cdot \frac{t}{V}\right)$$

$$\begin{bmatrix} \text{"Const.Q\_o (Pa-m\^3/s"} & \text{"PumpSpeed S\_o (m\^3/s)"} & \text{"check condition (almost zero)"} \\ Q_o & S_o & check \end{bmatrix}$$

Ex:

$q_1 := 2.5 \cdot 10^{-6}$ Pa-m/s t_prime := 3600 sec = 1 hr A := 6.23 m^2 V := 1.25 m^3

$p_u := 0.015 \cdot 10^{-3}$ Pa $t_1 := 14400$ sec..=4 hrs..outgassing const.

$p := 0.15 \cdot 10^{-3}$ Pa .... desired pressure t := 10800 sec = 3 hrs

Using the above Function, we get:

$$Sp\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, t) =$$

"Const.Q_o (Pa-m^3/s"	"PumpSpeed S_o (m^3/s)"	"check condition (almost zero)"
$1.99987 \cdot 10^{-5}$	0.07006	0

==========

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A simple EXCEL worksheet to do the above calculations is shown below:

F506 =(F498/F500)+F505*EXP(-F502/F500)/(F501-F499)

	C	D	E	F	G	H	I	J	K
492		**Pump down of a high vacuum system, where outgassing is considered (Ref: Barron):**							
493									
494		Inputs:							
495		Outgassing rate	q_1	2.50E-06	Pa-m/s				
496		Time at which q_1 is taken	t_prime	3600	s				
497		Area	A	6.23	m^2				
498		Volume	V	1.25	m^3				
499		Ultimate pressure	p_u	1.50E-05	Pa-m/s				
500		Outgassing const.	t_1	14400	s				
501		Working pressure	p	1.50E-04	Pa				
502		Time to attain p	t	10800	s				
503									
504		Outputs:							
505		Constant	Q_o	2.00E-05	Pa-m^3/s				
506		Pumping speed	S_o	7.006E-02	m^3/s				
507		Check the condition:	check	1.2714E-263	should be negligible				

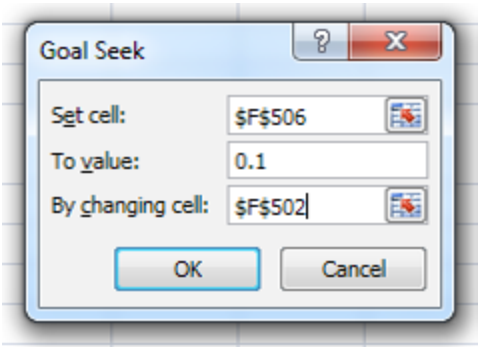
Formula applied to get the pumping speed can be read in the Formula bar.

And, the condition that

$$\exp\left(-S_o \cdot \frac{t}{V}\right) = 0$$

is also checked in the above worksheet.

It is also easy to find what will be the pump down time if the pumping speed is, say, 0.1 m^3/sec. Use Goal seek:



We get:

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	C	D	E	F	G	H	I	J	K
492		**Pump down of a high vacuum system, where outgassing is considered (Ref: Barron):**							
493									
494		Inputs:							
495		Outgassing rate	q_1	2.50E-06	Pa-m/s				
496		Time at which q_1 is taken	t_prime	3600	s				
497		Area	A	6.23	m^2				
498		Volume	V	1.25	m^3				
499		Ultimate pressure	p_u	1.50E-05	Pa-m/s				
500		Outgassing const.	t_1	14400	s				
501		Working pressure	p	1.50E-04	Pa				
502		Time to attain p	t	5687.764576	s				
503									
504		Outputs:							
505		Constant	Q_o	2.00E-05	Pa-m^3/s				
506		Pumping speed	S_o	9.989E-02	m^3/s				
507		Check the condition:	check	4.0865E-198	should be negligible				
508									

We see that time required will be 5687.76 sec = 1.58 hrs.

Write a Mathcad Function to find pump down time in high vacuum region when pump speed S_p is given:

$q_1 := 2.5 \cdot 10^{-6}$ Pa-m/s t_prime := 3600 sec = 1 hr A := 6.23 m^2 V := 1.25 m^3

$p_u := 0.015 \cdot 10^{-3}$ Pa $t_1 := 14400$ sec..=4 hrs..outgassing const.

$p := 0.15 \cdot 10^{-3}$ Pa .... desired pressure t := 108 sec ...guess value

$S_p := 0.07006247$ m^3/s

Given

$S_p = Sp\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, t)_{1,1}$

$Time\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, S_p) := Find(t)$

i.e.

$Time\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, S_p) = 1.08000005 \cdot 10^4$ sec.

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Ex: When Sp = 0.1 m^3/s, what is the pump down time?

$S_p := 0.1$ m^3/s

Using the above Fumction, we get:

$\text{Time\_pumpdown\_to\_high\_vacuum}(q_1, t\_prime, A, V, p_u, t_1, p, S_p) = 5.67137969 \cdot 10^3$ sec.

One more Ex: If Sp = 0.06 m^3/s, what is the pump down time?

$S_p := 0.06$ m^3/s

Then, using the Function, we get:

$\text{Time\_pumpdown\_to\_high\_vacuum}(q_1, t\_prime, A, V, p_u, t_1, p, S_p) = 1.30356117 \cdot 10^4$ sec.

7.6 CALCULATION OF CONDUCTANCES AND PUMP DOWN TIME USING NOMOGRAMS

We can quickly determine the conductances and pump down times by the use of Nomograms:

Following are from Leybolds Fundamentals:

Tube data, and Conductances for Laminar flow (with average pressure p_bar = 1 mbar) and Molecular flow, for air at 20 C are given below:

Tube data:

DN	DN	mm ID
10		10
16		16
	20	21
25		24
	32	34
40		41
	50	51
63		70
	80	83
100		102
	125	127
160		153
	200	213
250		261
	320	318
400		400
	500	501
630		651
	800	800
1000		1000

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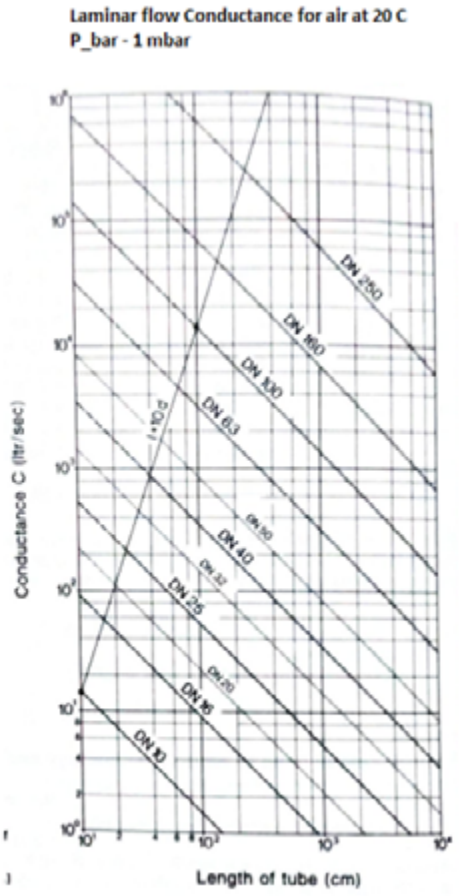

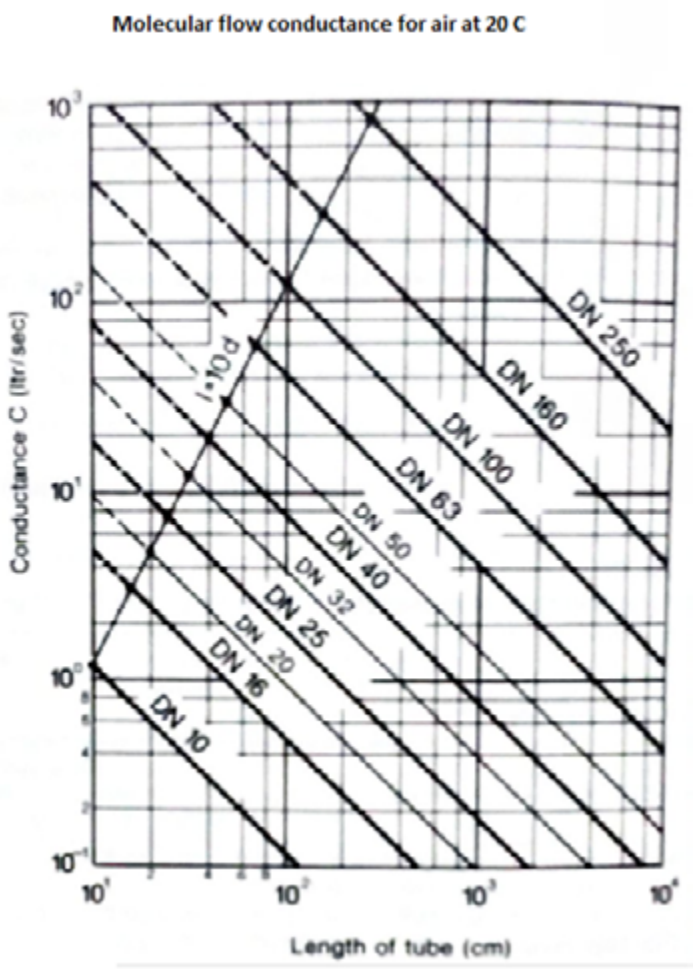

Conductances for air at 20 C, in Viscous flow region, flowing in a pipe [4]:

To find the conductance of pipes in viscous flow region, Nomogram of Harries (1949) is well known, and is shown below: Here, P_bar = average pressure, C = conductance, and

A = P_bar / C. This nomogram helps to determine the dia D and length L of the connecting pipe between the vacuum pump (whose pumping speed is Sp at the inlet pressure P) and the chamber to be evacuated, **such that the pumping speed at the chamber is (0.3 x Sp).** As an example, line joining L = 9 m and D = 5 cm, intersects the A scale at point F. For an inlet pressure of P = 0.1 torr, connect this point and F, and extend it to read the admissible max speed Sp = 60 m^3/hr.

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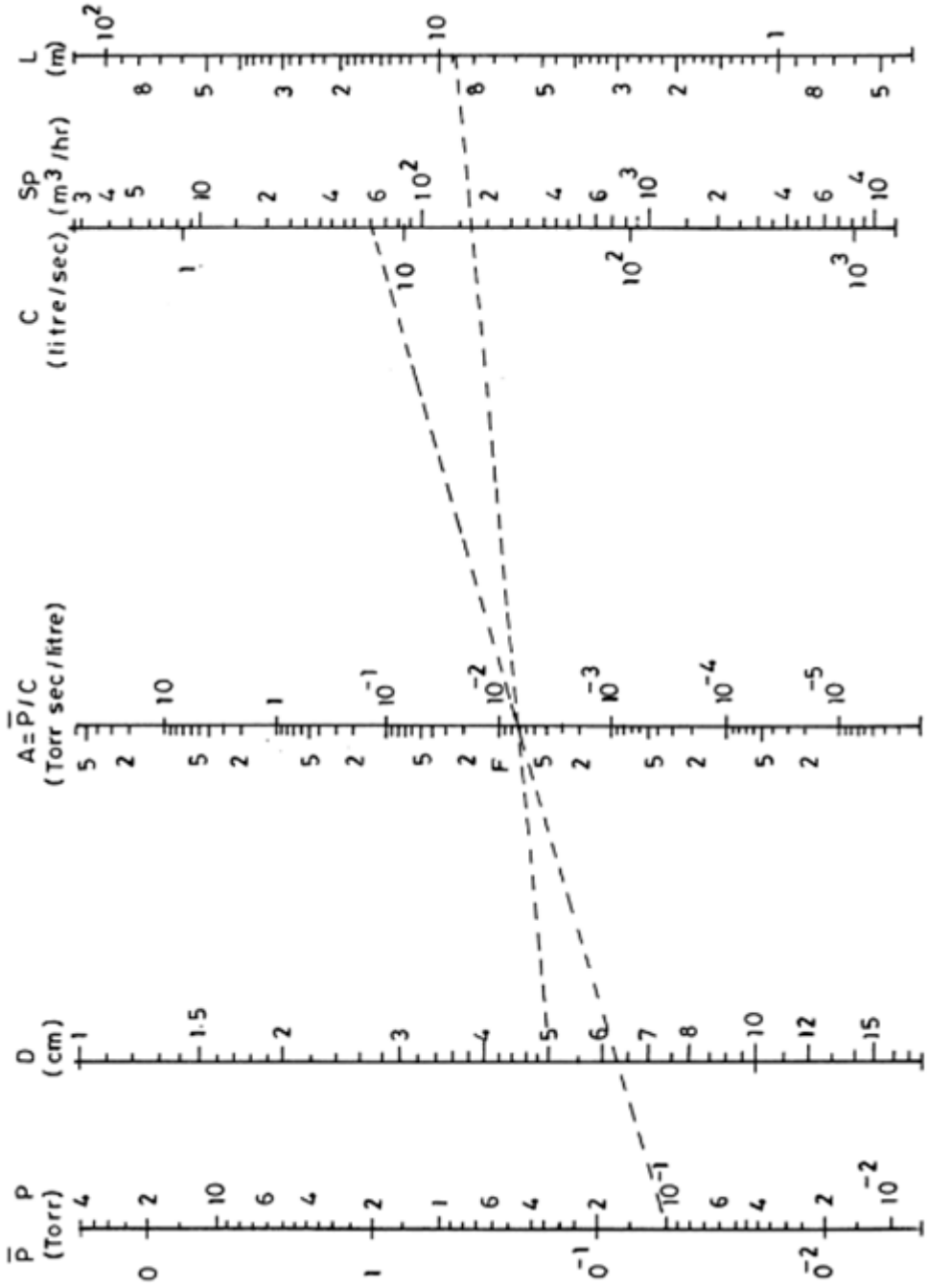

Fig. Nomogram for evaluation of pipe conductance in viscous flow for air at 20 C.

Nomogram to determine Conductances of pipes for air at 20 C, in Molecular flow region:

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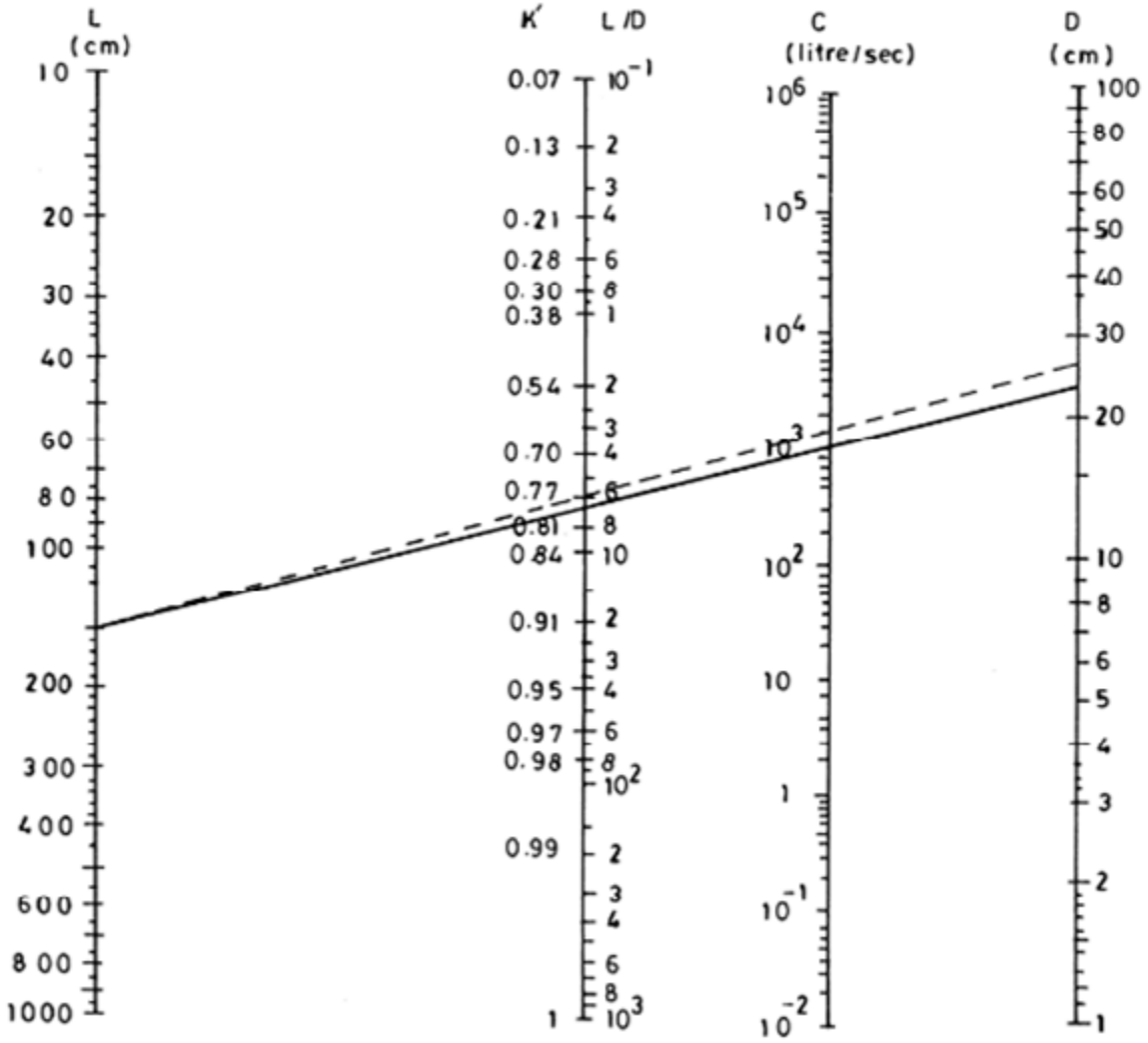

This Nomogram was developed by Delafosse and Mongodin (1961).

It gives correlation between L, D and C. Also, gives correction factor K' for a 'short' pipe.

As an example: to determine required D for a long pipe of length L = 1.5 m to have a conductance of C = 1000 lit/s, in the molecular flow range, draw a line through the points L=150 cm and C=1000 lit/s, and note that it cuts the scale of D at 24 cm. L/D is about 7 and the correction factor for short pipe, K' is read off as 0.79.

Therefore, after correction, the real conductance for pipe is: C = 1000 x 0.79 = 790 lit/s.

Conductances for air at 20 C, in whole pressure range:

This Nomogram was also presented by Delafosse and Mongodin (1961), and evaluates the conductance for flow of air at 20 C through circular pipe.

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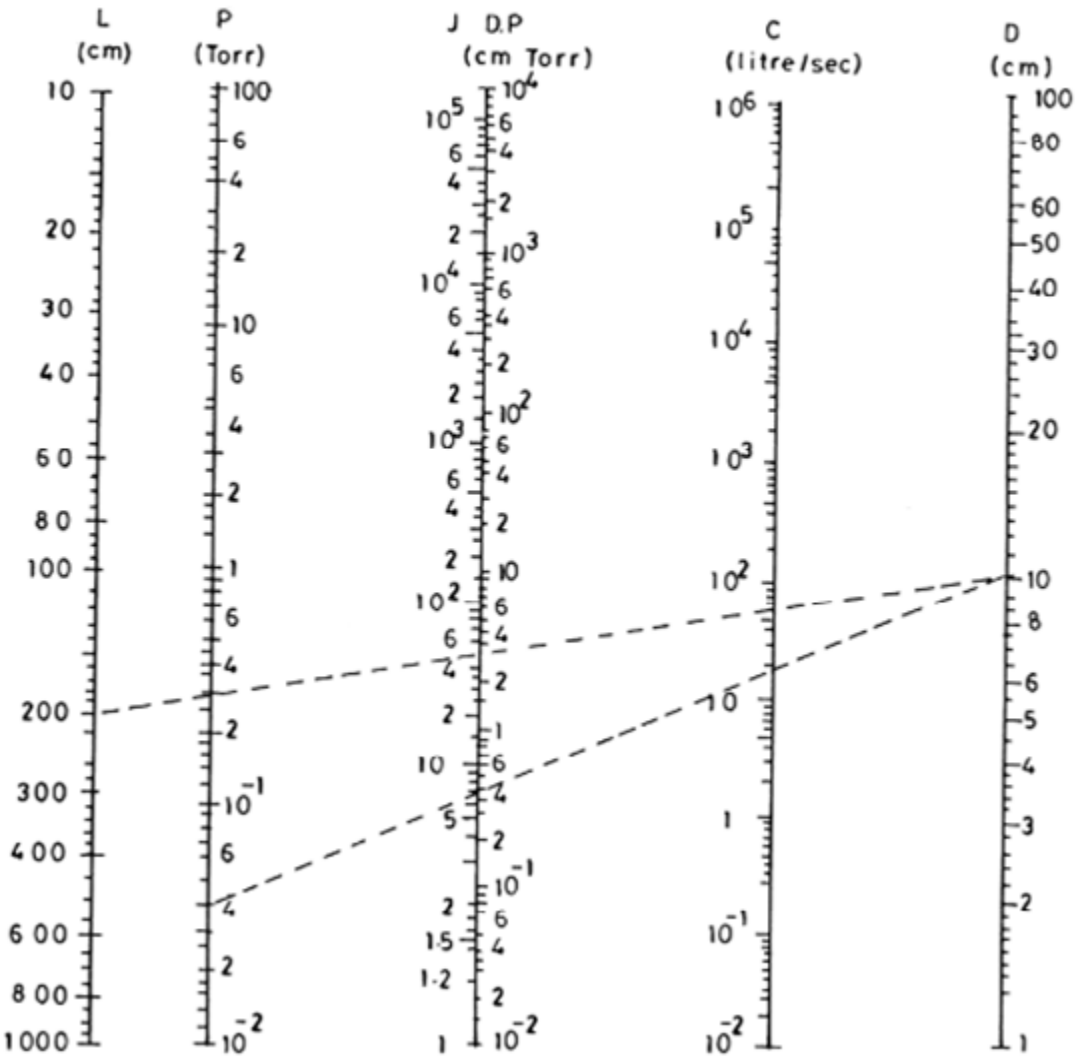

Example:

Pipe length L = 2 m, D = 10 cm, and straight line joining these points cuts C scale at C = 60 lit/s. If the average pressure P_bar = 4 x 10^{-2} torr, join this point to the D = 10 cm point, and read the correction factor for this DP_bar on the J scale as 6.8 (see the lower line in the above fig.). Then, the corrected conductance is: C = 60 x 6.8 = 408 lit/s.

Nomogram to evaluate the *pump down time* for air at 20 C, in Molecular flow region:

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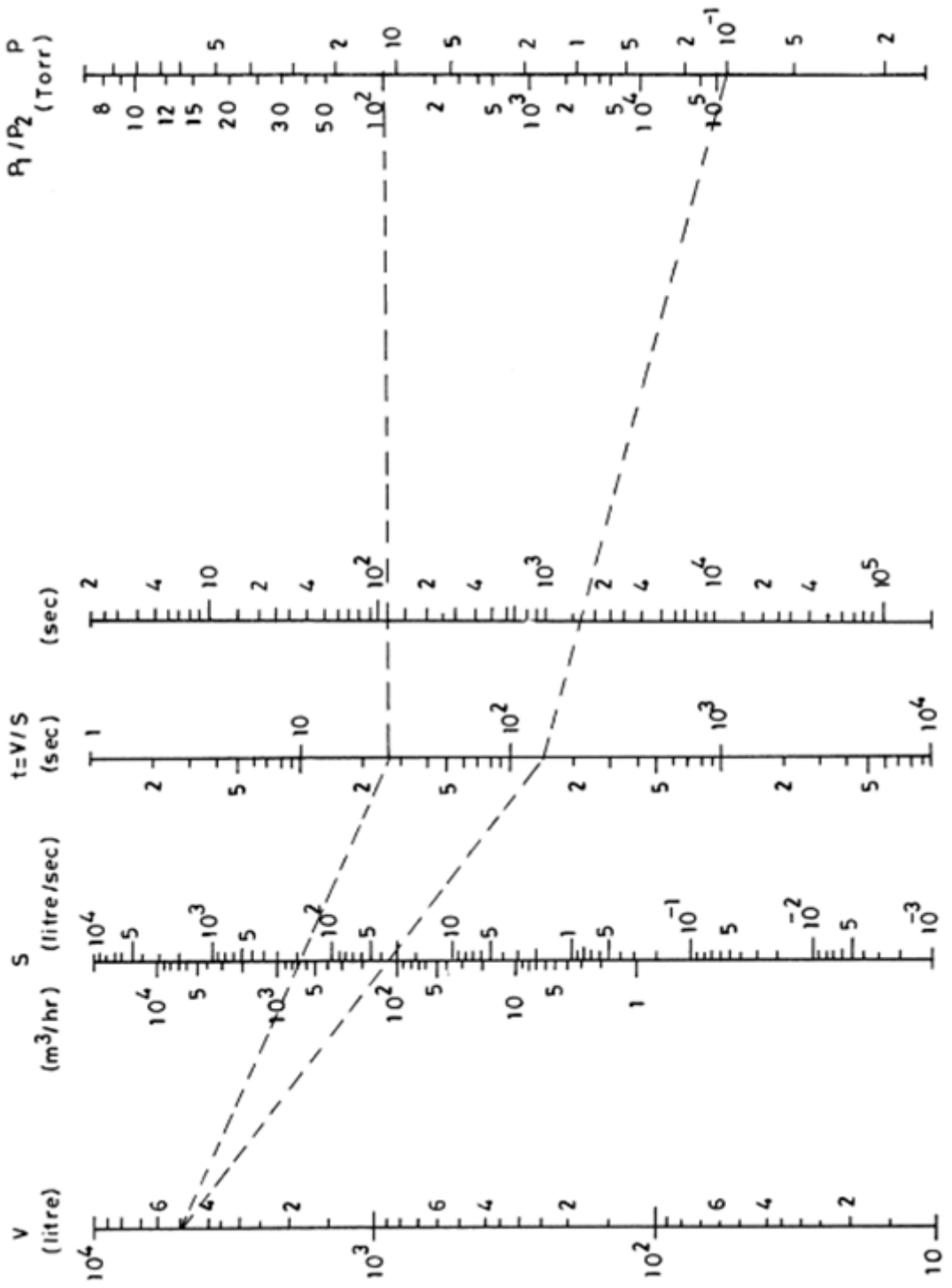

Ex. 1: (see lower lines in fig.): For a volume V = 5000 lit and pumping speed S = 120 m3/hr, the line connecting these points is extended to get the time-constant t line (τ = V/S) at τ = 140 s. If the final pressure desired is P = 10^{-1} torr, starting with initial pressure of 760 torr, then connecting points τ and P gives pump down time as t = 1800 s.

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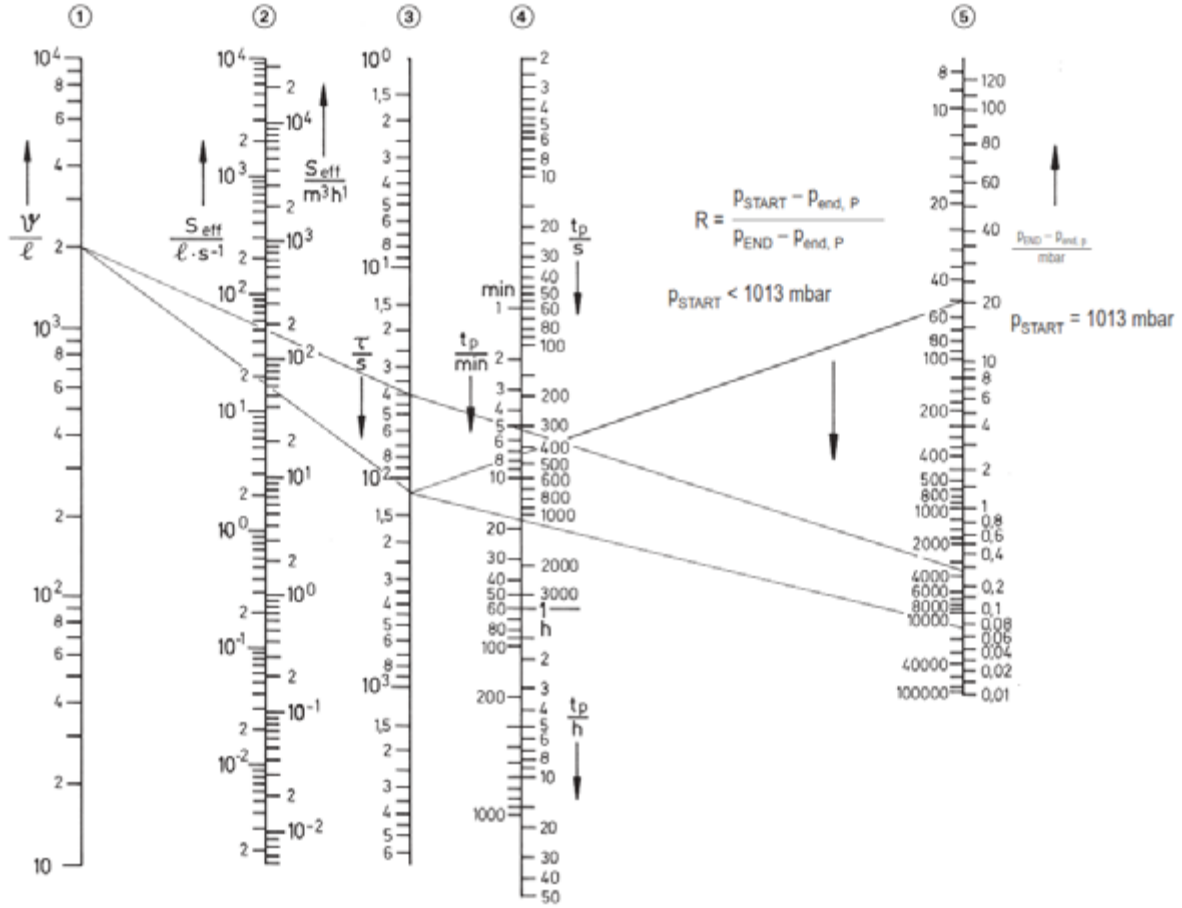
Ex. 2: (see upper lines in fig.): If volume V = 5000 lit, and a pump speed S = 700 m^3/hr, then, time constant τ = 25 s. If this pump is used to decrease the pressure from 10^{-1} torr to 10^{-3} torr, i.e. (P1/P2 = 100), the pump down time is obtained by joining the points on time constant scale and (P1/P2) scale, and reading the pump down time as 120 s in the time scale.

Two additional Nomograms are given for pump down time: (Ref: Leybolds Fundamentals)

A. To determine pump down time of a vessel in rough vacuum pressure range:



Example 1: A vessel with volume V = 2000 lit is to be pumped down from P_{start} = 1000 mbar (atm) to P_{end} = 10^{-2} mbar by a Rotary plunger pump with an effective pumping speed at the vessel = S_{effmax} = 60 m^3/hr = 16.7 lit/s. The pump down time can be obtained from the Nomogram in two steps:

1. **Determine τ:** A straight line is drawn through V =2000lit (column 1) and S_{eff} = 60 m^3/hr = 16.7 lit/s (column 2) and τ = 120s = 2 min is read off in column 3.(uncertainty in reading is about 10%).

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2. **Determination of tp:** The ultimate pressure of the pump is p_{ultp} = 3 x 10^{-2} mbar, apparatus is clean and leakage negligible (set q_{pvin} = 0).Then, $p_{end} - p_{ultp}$ = (10^{-1} - 3 x 10^{-2}) mbar = 7 x 10^{-2} mbar. Now a straight line is drawn through the point found under step 1, τ = 120 s (column 3) and $p_{end} - p_{ultp}$ = 7 x 10^{-2} mbar in column 5, and this line cuts column 4 to give pump down time t_p = 1100 s = 18.5 min.(uncertainty is about 15 %). Thus, taking care of uncertainties, we can say, t_p = 18.5 x 1.3 = 25 min.

Example 2: A clean and dry vacuum system (qvin = 0) with V = 2000 lit is to be pumped to a pressure p_{end} = 10^{-2} mbar. Since this pressure is smaller than the ultimate pressure of rotary piston pump, a Roots pump must be used with the rotary pump. Roots pump has a starting pressure of p1 = 20 mbar, pumping speed of S_{effmax} = 200 m^3/hr = 55 lit/s as well as p_{ultp} = 4 x 10^{-3} mbar. From p_{start} = 1000 mbar to p = 20 mbar one works with rotary pump, and then connects to Roots pump from p1 = 20 mbar to p_{end} = 10^{-2} mbar, where rotary pump acts as backing pump. For the first pumping step, one obtained time constant τ as 120 s = 2 min from the nomogram (example 1). If this point in column 3 is connected with $p_1 - p_{ultp}$ = (20 - 3 x 10^{-2}) mbar = 20 mbar (ignoring p_{ultp} since rotary pump has const pumping speed over the entire range of 1000 mbar to 20 mbar), one gets t_{p1} = 7.7 min. The Roots pump must reduce the pressure from p1 = 20 mbar to p_{end} = 10^{-2} mbar. i.e. the pressure reduction ratio is 3300.

The time constant is obtained as 37 s in column 3, for V = 2000 lit (column 1) and S_{eff} = 55 lit/s (column 2). If this point in column 3 is connected to R = 3300 in column 5, one obtains t_{p2} = 290 s = 4.8 min in column 4. Thus, also taking 1 min for change over time, total pump down time is t_p =(7.7 min + 1 min + 4.8 min) = 13.5 min.

B. To determine pump down time in medium vacuum range, taking in to account the out-gassing from walls:

This Nomogram gives the relationship between Sp of the pump, Volume (V), Surface area (F), Nature of inner surface, i. e. Out-gassing rate, and the pump down time from 10 mbar to 10^{-3} mbar.

Example 1:

Chamber volume, V = 70 m^3

Inner surface area, F = 100 m^2

Gas evolution = 2 x 10^{-3} mbar.l/s/m^2

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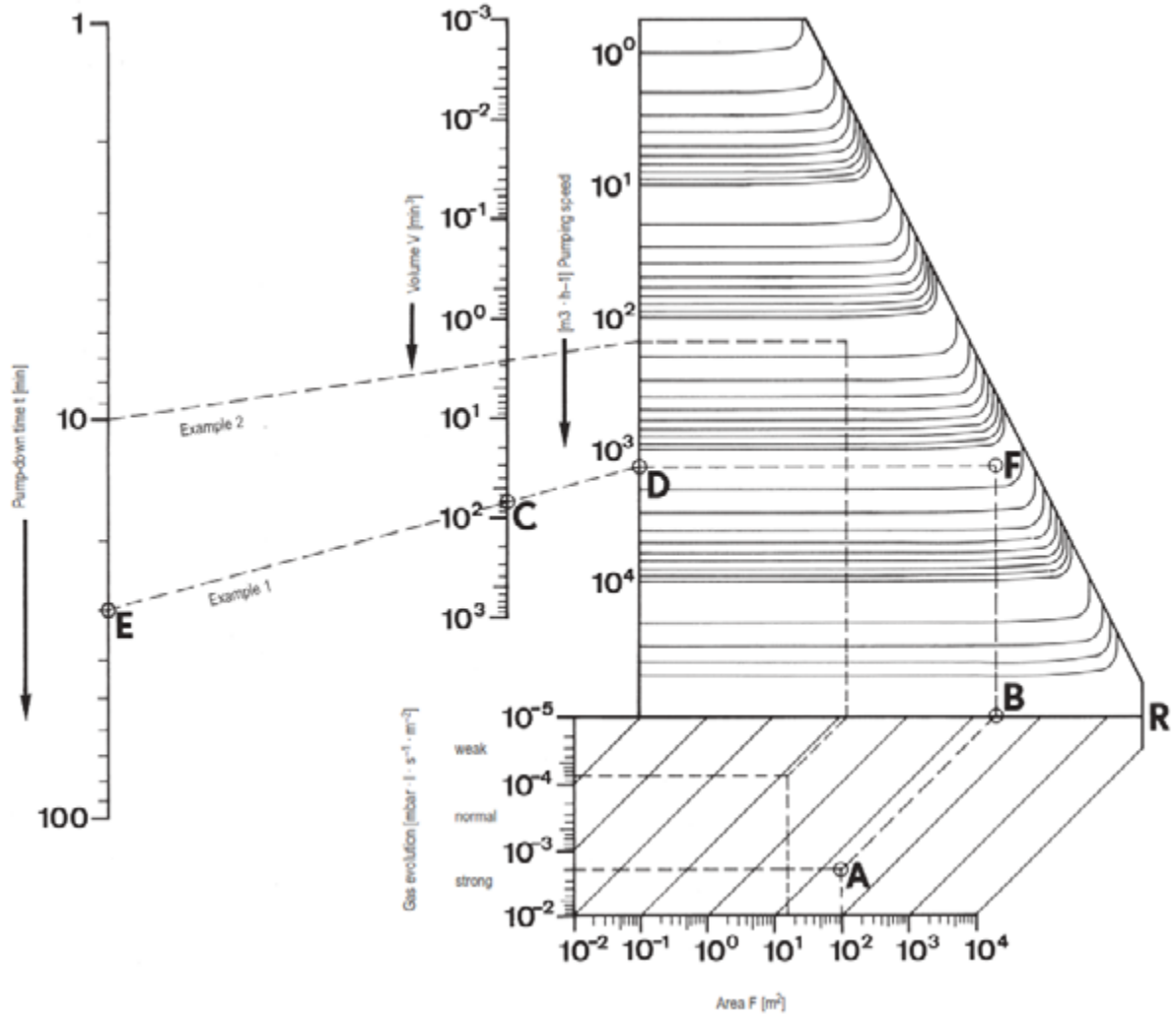
Decide if a pump with a nominal pumping speed Sp = 1300 m^3/hr is suitable to reduce pressure from 10 mbar to 10^{-3} mbar.

Solution:

Coordinates of given values of surface area (= 100 m^2) and gas evolution (2 x 10^{-3} mbar.l/s/m^2) intersect at A, joined to point B by upward sloping line, and then connected via the vertical line to the curve based on the pumping speed of the pump (1300 m^3/hr) (point D).



If the projection from D is within the marked curve area (F), then the pump is adequate to handle gas evolution. Pump down time from 10 mbar to 10-3 mbar is then given as 30 min by connecting point D (i.e. representing Sp=1300 m^3/hr) and point C (representing volume V = 70 m^3) and extending to read the pump down time (point E).

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Example 2:

Here, volume V = 3 m^3, Surface area F = 16 m^2

Gas evolution = 8 x 10^{-5} mbar.l/s/m^2

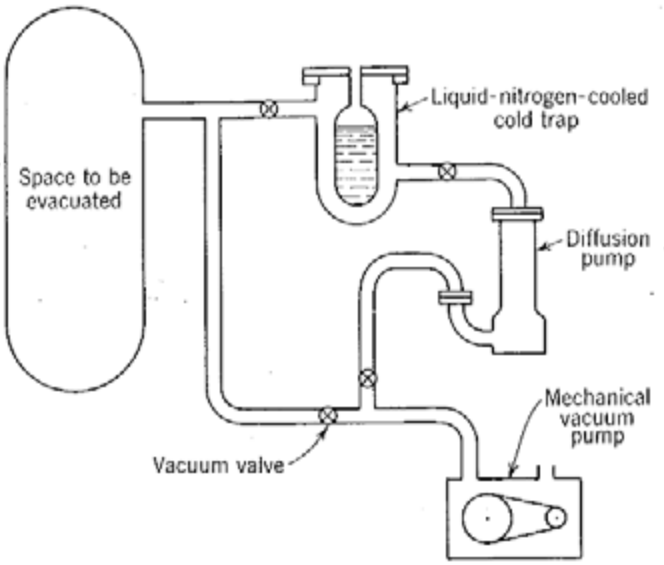
Find the Sp of the pump required to reduce pressure from 10 mbar to 10^{-3} mbar within 10 min.

Solution: The steps are shown in the Nomogram, similar to Example 1. We see that the Sp required is about 150 m^3/hr.

7.7 COMPONENTS OF VACUUM SYSTEMS [1]

Note: Components of vacuum systems include: vacuum pumps, baffles, valves, cold traps, vacuum measuring gauges etc. Topics on Vacuum system components (except Cryopumps) and Vacuum measurement, do not strictly come under the purview of this book. So, we will cover these topics briefly, for sake of completeness. For more information on these topics, interested reader should refer to the books or publications referenced at the end of this ebook.

7.7.1 BASIC ELEMENTS OF A TYPICAL VACUUM SYSTEM



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The essential elements of a vacuum system are shown in Fig. above.

A mechanical vacuum pump is used as roughing pump to reduce the system pressure to approximately 1.0 Pa (about 10^{-2} torr) through a by-pass line. When the pressure is reduced to about 1 Pa, the diffusion pump is turned on and the valve in the by-pass line is closed. The diffusion pump needs the pump exhaust pressure to be below about 10 Pa (about 10^{-1} torr) to operate; so, the forepump is necessary. In addition, the valving shown is such that the diffusion pump may be isolated from the remainder of the system. A cold trap or baffle is provided near the inlet of the diffusion pump to prevent back-streaming of oil vapor and to freeze out condensable gases such as water vapor.

For a well-trapped, clean system, pressures between 0.10 mPa and 0.01 mPa (about 10^{-6} to 10^{-7} torr) may be attained with a diffusion pump.

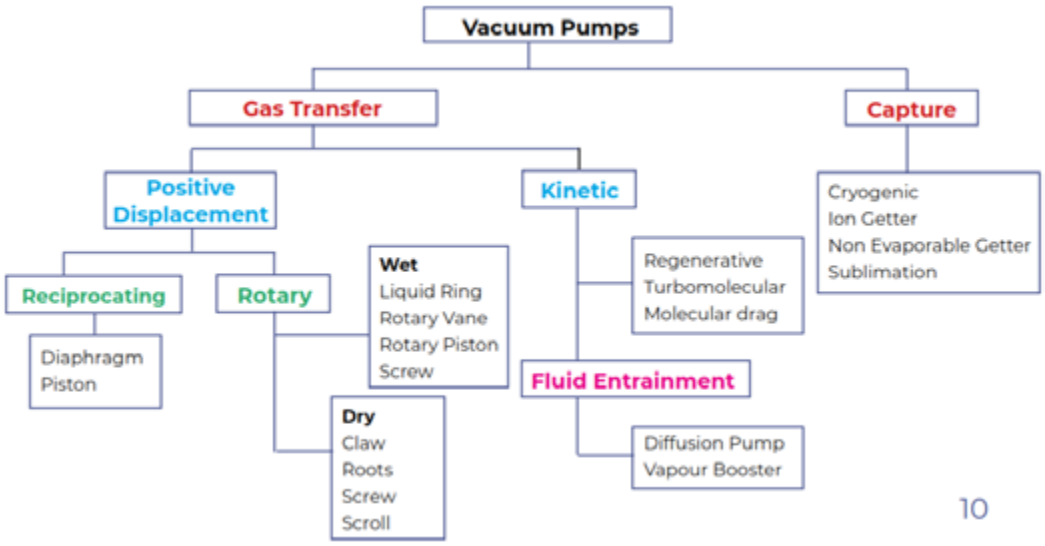
If lower pressures are desired, an ion pump or a cryopump must be installed in addition to the diffusion pump and mechanical pump. For the effective operation of evacuated insulations, vacuum pressure levels of this magnitude are not generally required.

Classification and typical operating ranges of various vacuum pumps are shown in Figs below:

7.7.2 VACUUM PUMPS

(Ref: Vacuumscienceworld.com)

Classification of vacuum pumps:



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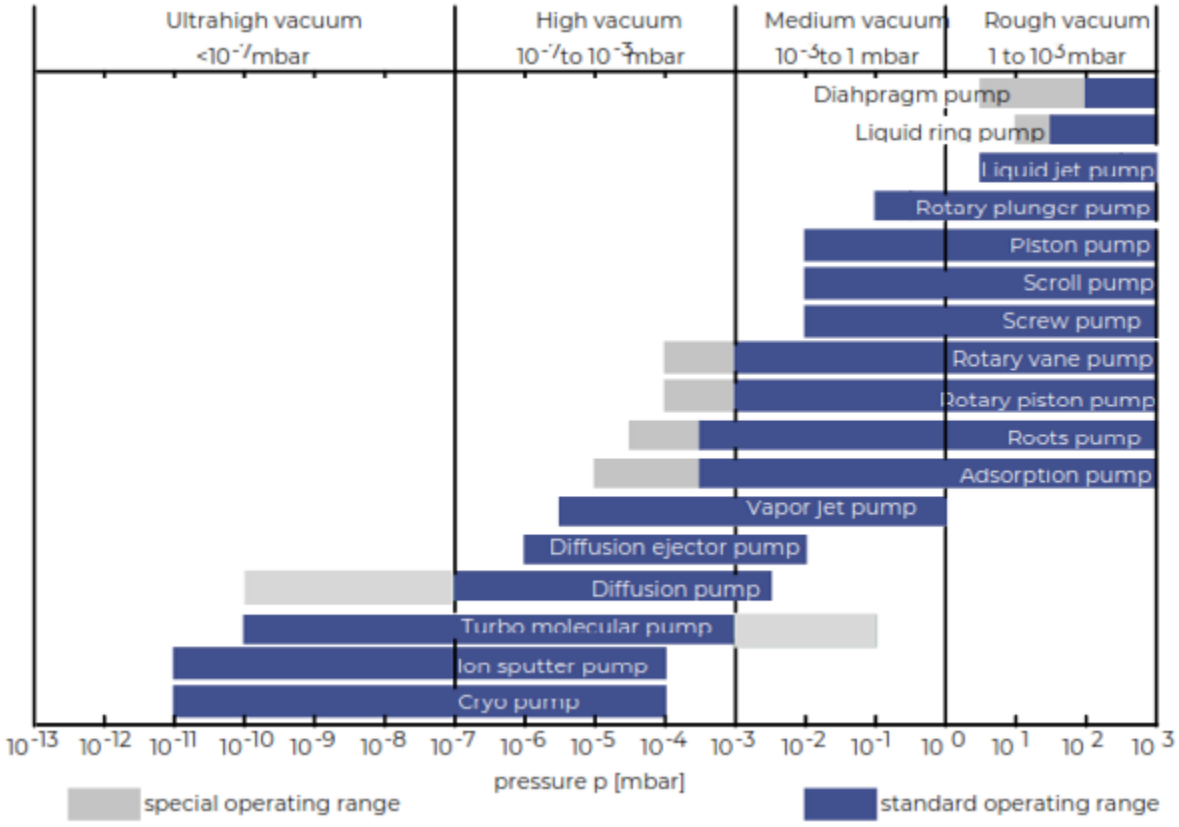
Operating ranges:

Typically, the different pressure ranges in vacuum technology are defined as follows: rough vacuum (from 10^{3} mbar to 1 mbar); medium vacuum (1 mbar to 10^{-3} mbar); high vacuum (10^{-3} mbar to 10^{-7} mbar); ultra-high vacuum (10^{-7} mbar to 10^{-12}); and extreme high vacuum (less than 10^{-12} mbar) (see diagram below).

Working ranges:



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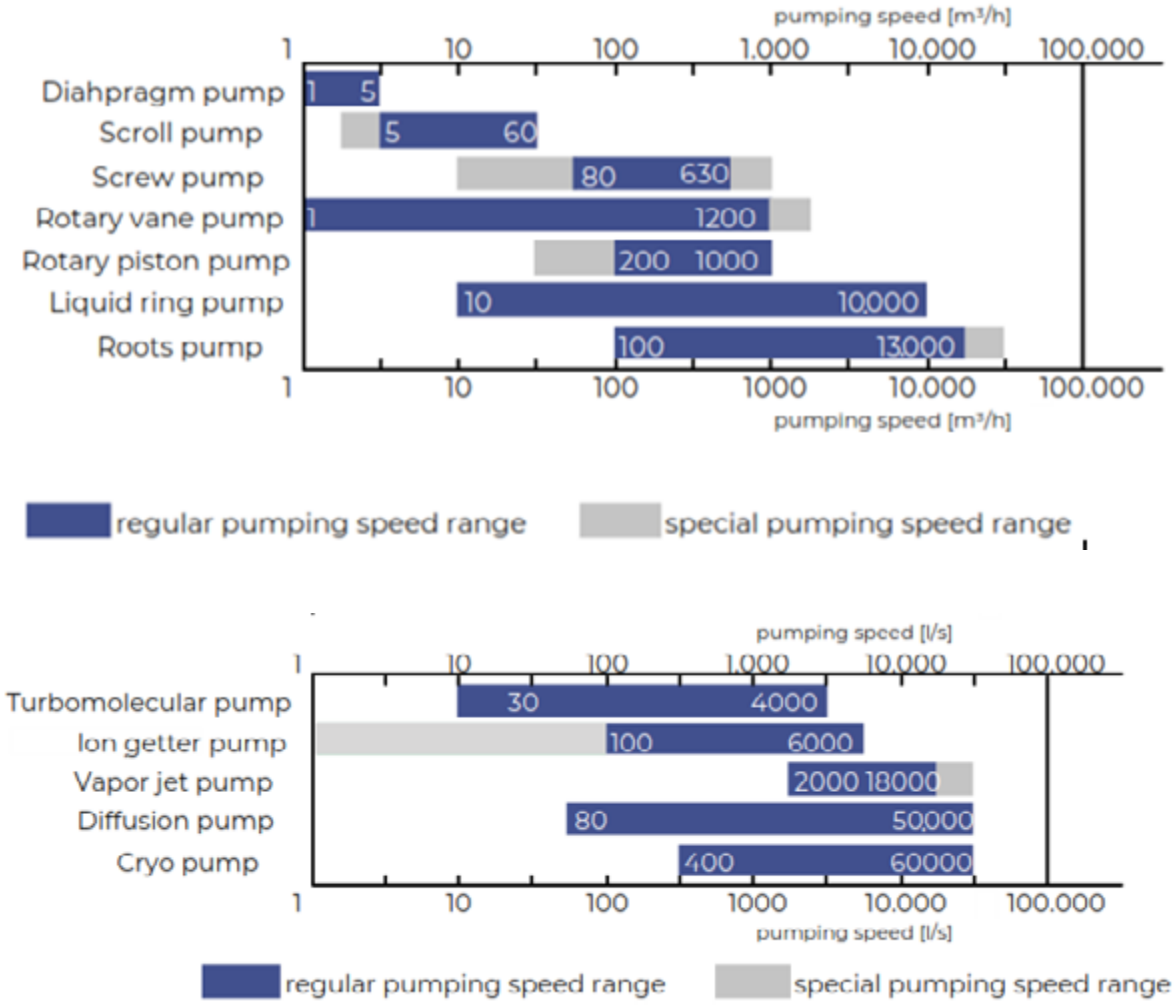
Pumping speed ranges:



A. Mechanical vacuum pumps:

A typical mechanical vacuum pump (Rotary vane type pump) is shown in Fig. below. The pump speed versus pressure curves for this type of pump are also shown:

Rotary vane type mechanical pump:

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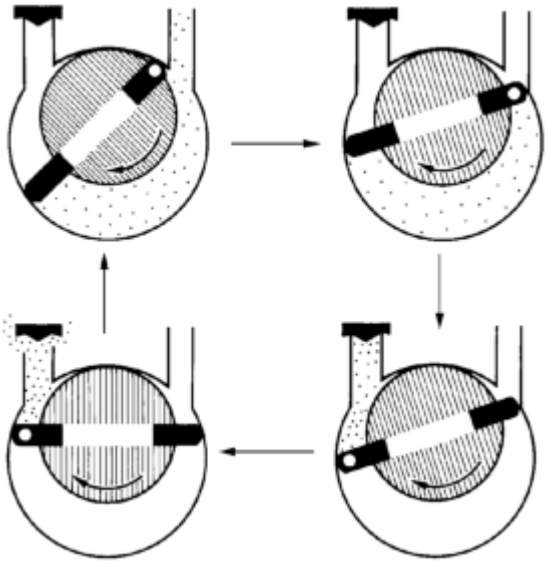
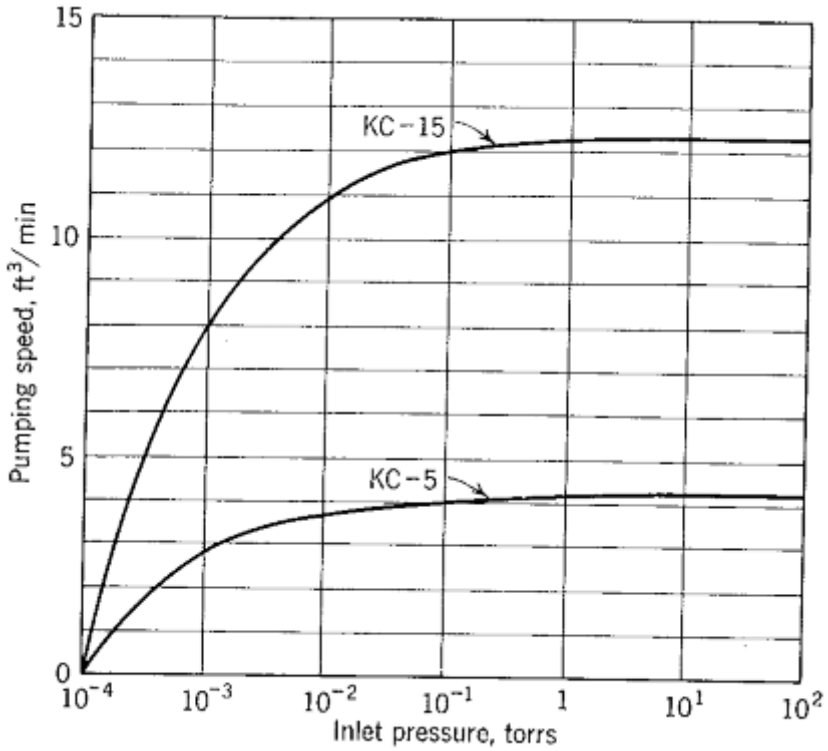


Pressure range: Atmosphere to 10^{-4} mbar.
Excellent reliability, robust, compact and economical.
High compression ratios, and better internal cooling because of oil sealing.
No hydrocarbon free vacuum, and requires oil changes.
Usual backing pump in many high vacuum applications.

Pumping speed curves (Kinney mechanical pumps)[1]:



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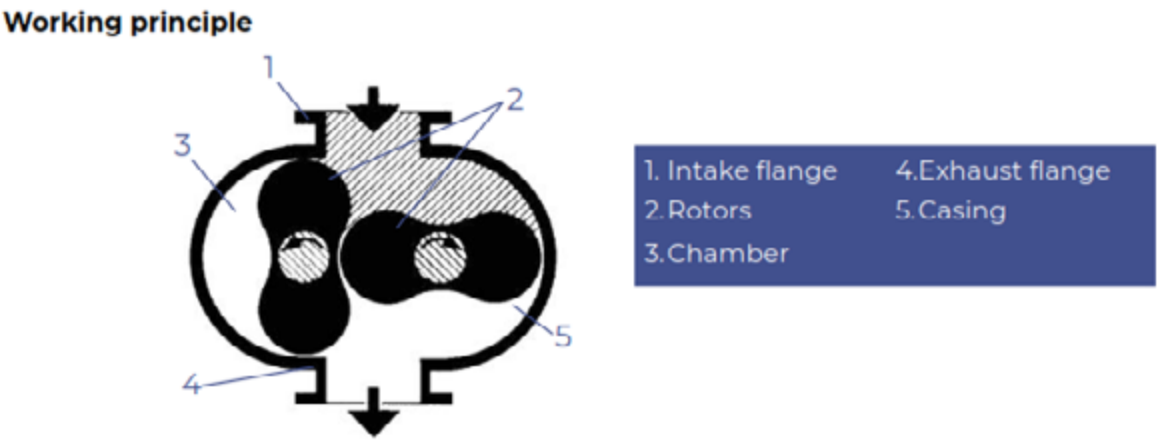
1. **For Animation video of the working of a Rotary (vane) pump, see the following link:**
   http://www.youtube.com/watch?v=AFHogF-9eGA&hd=1
2. **Animation video of the working of a Trivac Rotary (vane) pump:**
   http://www.youtube.com/watch?v=IIKOx0JqE08

B. Roots blowers:

(Ref: Vacuumscienceworld.com)

It contains two impellors, each shaped like a figure 8—that rotate in opposite directions. As the two lobes rotate, trapped air is compressed to the exhaust pressure. The blower is **well-suited for handling large** flow **rates**.



Ref: Leybolds:

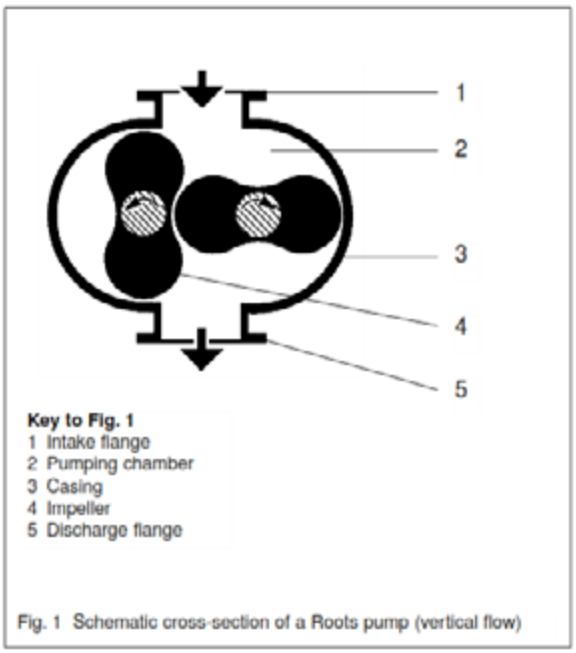


Fig. 1 Schematic cross-section of a Roots pump (vertical flow)

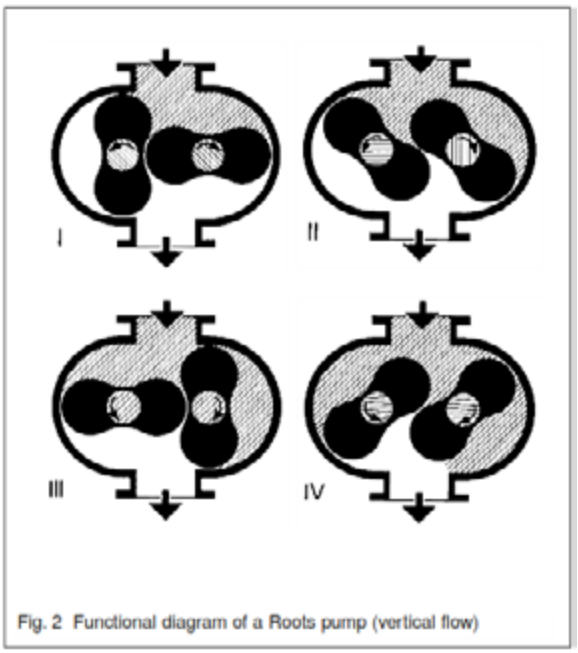


Fig. 2 Functional diagram of a Roots pump (vertical flow)

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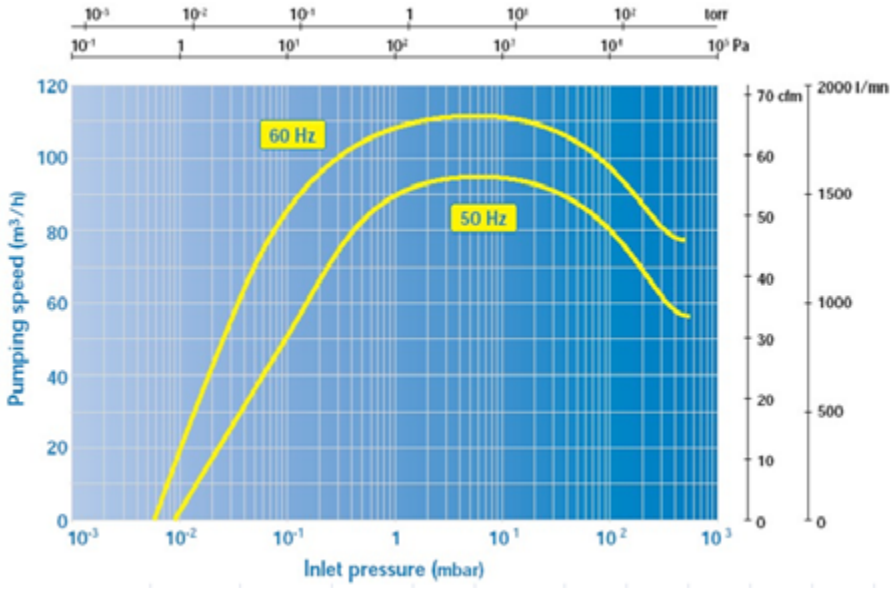
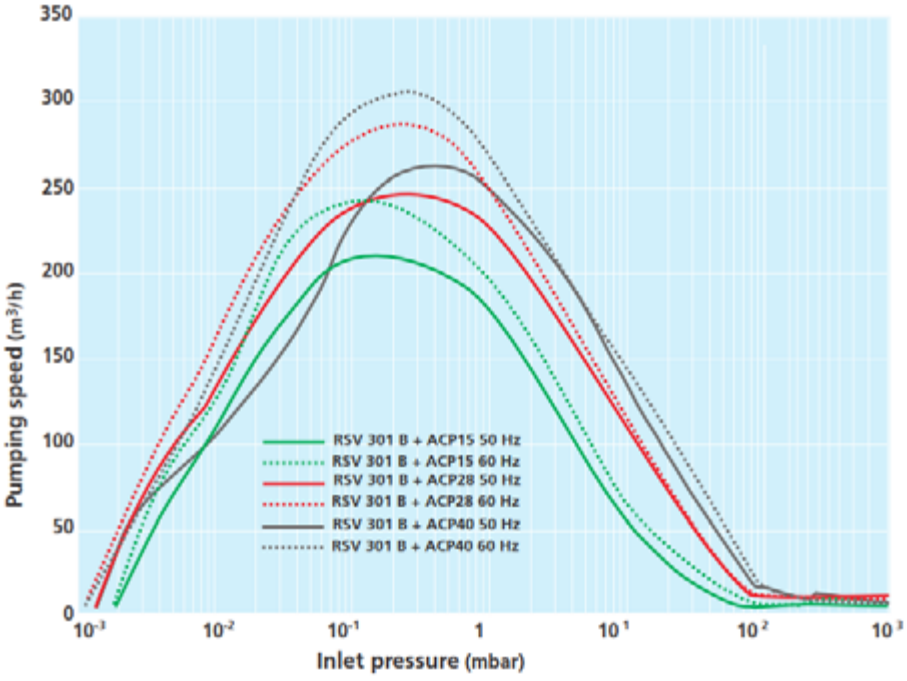
The advantages of Roots pumps are that they are very quiet and compact, enjoy a long service life, there are no contacting parts, and they provide clean pumping (i.e. there are no particles or oils to contaminate the vacuum system). A roots-fore pump combination is typically a more economical option for improved pumping speeds and ultimate pressures compared to a bigger sized discrete fore pump. However, the limited compression ability means that a Roots booster pump always needs a fore pump for operation.

Typical pumping speed curves (bell shaped) for Alcatel Booster (ADP 122 P or L) pumps are shown below:



Pumping speed curves for a few more models are also shown below:


RSV 301 B + ACP15 50 Hz
RSV 301 B + ACP15 60 Hz
RSV 301 B + ACP28 50 Hz
RSV 301 B + ACP28 60 Hz
RSV 301 B + ACP40 50 Hz
RSV 301 B + ACP40 60 Hz
Pumping speed (m³/h)
Inlet pressure (mbar)

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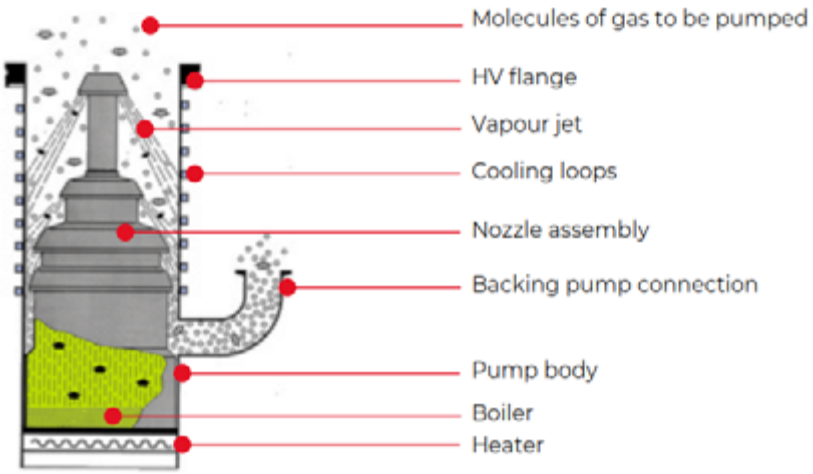
C. Diffusion pumps:(Ref: Vacuumscienceworld.com)



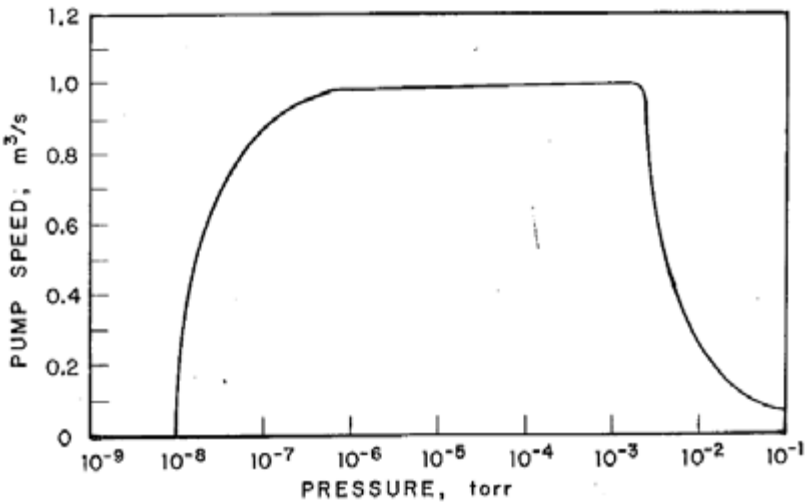
They use a high velocity vapor jet to direct the gas molecules from pump inlet to downwards and then to exhaust. Used both in industry and research, and for pressures < 10^{-8} mbar. They have high pumping speeds, are cheap, **but need a backing pump** to operate. Backing pressure is about 1 or 2 Pa (about 0.01 torr).

Advantages: Relatively low cost; no vibration, pumps all gases, tolerance against radiation, magnetic fields.

Oil of low vapor pressure is used, generally silicone oil or polyphenyl ethers. The oil is heated by a heater at the bottom and the generated vapors are passed through series of nozzles to produce high velocity jets. Outside of pump is cooled by circulating water in tubes.

Back-streaming of oil vapors is reduced by using a LN2 trap.

Pumping speed of a Diffusion pump of nominal diameter of 100 mm is shown below [1]:



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Note[1]: In the ideal case, the diffusion pump should remove gas molecules as fast as they come in to the pump inlet; i.e. max pumping speed is the conductance of inlet aperture, viz.

$$S_{p\_orifice} = \left(\frac{\pi \cdot R_u \cdot T}{32 \cdot M}\right)^{\frac{1}{2}} \cdot D^2 \qquad \text{where D = dia of pump inlet}$$

But, actual pump speed is less than this value, and is given by:

$$S_p = H_o \cdot S_{p\_orifice}$$

where Ho is known as **'Ho coefficient'.** For commercial vacuum pumps, Ho coeff ranges from 0.4 to 0.55.

For Animation video of the working of a Diffusion pump, see the following link:

http://www.edwardsvacuum.com/uploadedFiles/Resource/Corporate/About_Us/diffusion_pump.swf

D. Turbo-molecular Pumps (TMPs): (Ref: Vacuumscienceworld.com)

It has a rotor spinning at very high speeds (24,000 to 90,000 rpm). Similar to a multi-bladed turbine, with pairs of stator and rotor placed along the shaft.

They work by transferring high speed impact to the gas molecules and pushing them to exit. They operate in the molecular flow range from 10^{-3} to 10^{-11} mbar, and need a backing pump to operate.

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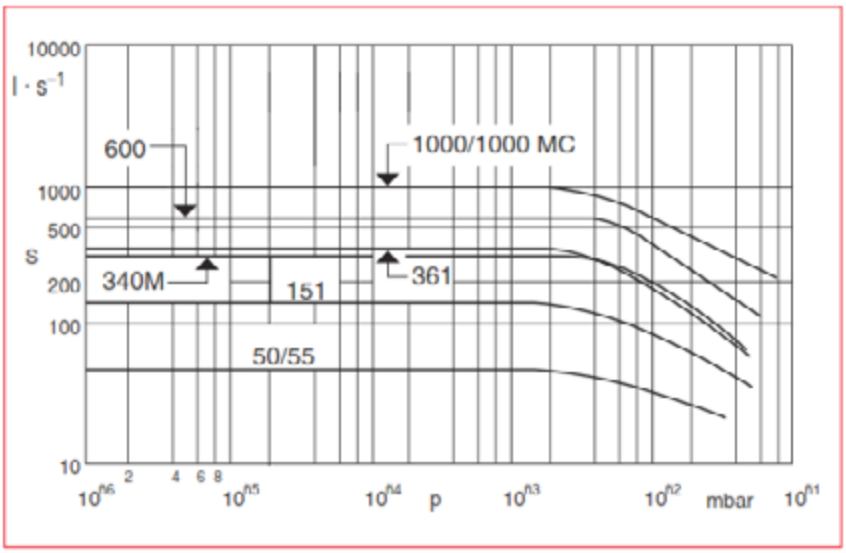
Because of high speeds of operation, design of rotor bearings is important. Three methods used are: (i) 5 axis, active, magnetic levitated bearing design (ii) all mechanical bearing design, and (iii) combination of passive magnetic and mechanical bearing design.

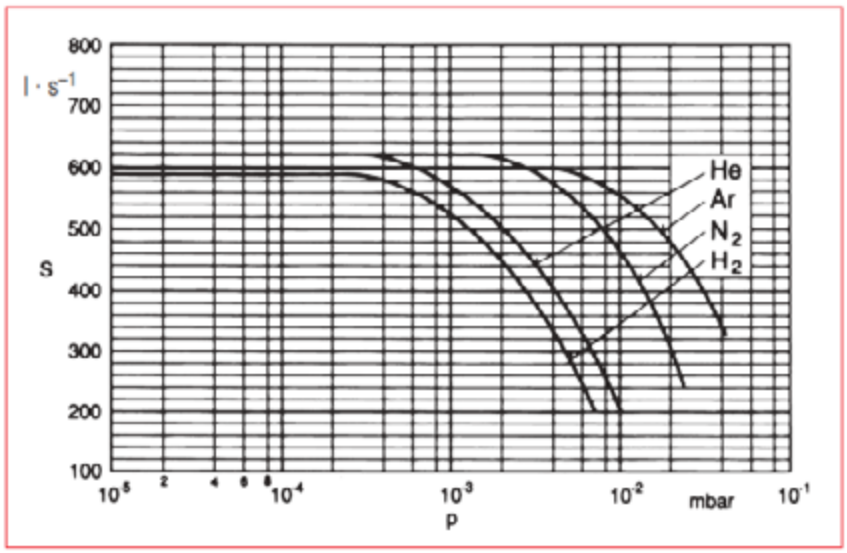
Advantages: High pumping speeds at HV/UHV, easy operation, hydrocarbon free, low maintenance, starts working at high pressures (molecular regime).

Disadvantages: Less pumping speed for light gases, moving parts are a source of vibration, sensitive to mechanical shocks, requires backing pump.

Pumping speeds for air for different models of Leybold TMPs are shown below:



Pumping speeds for different gases for model Turbovac 600 are compared below:



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1. **Video of the working of Oerlikon-Leybold Turbo-Molecular Pump:** http://www.youtube.com/watch?v=XOca57gPsq4
2. **Video of the working of Agilent Vacuum TechnologyTurbo-Molecular Pump:** http://www.youtube.com/watch?v=xIfOHrXyoJo

E. Ion Getter (or, Sputter ion) Pumps (IGP):

(Ref: Vacuumscienceworld.com)

It is an array of Penning cells where a gas discharge is generated by a high magnetic field and electrical potential. By this, gas molecules are ionized and implanted on the cathode, causing sputtering of the cathode material, which forms an active gettering layer.

IGPs are capable of producing very low ultimate pressures, viz. 10^{-5} to 10^{-11} mbar.

Advantages: Very low ultimate pressures,, hydrocarbon free vacuum, high temp tolerance (bakable), No moving parts, no valves, low maintenance.

Disadvantages: Low pumping speed for noble gases, decreasing pumping speed in UHV range, needs high voltage and magnetic field, needs a roughing pump, heavy weight.

Ref: Sputter ion pumps by L. Schulz, Switzerland:

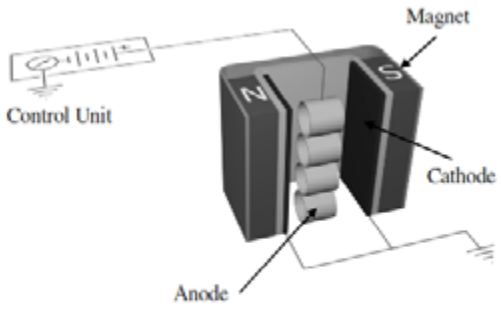

Fig. 1 Configuration of a sputter-ion pump.

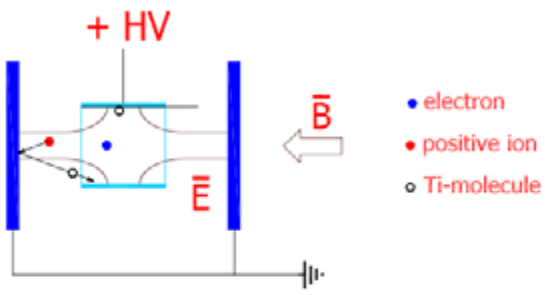

Fig. 2 Penning cell.

Pumping effect is selective for different types of gas.

Pumping speed vs pressure for a standard diode, for air:

Pumping speed of an ion getter pump varies with speed. Also operating pressure must be less than 10^{-4} mbar; otherwise, space charge in Penning cells changes to a glow discharge

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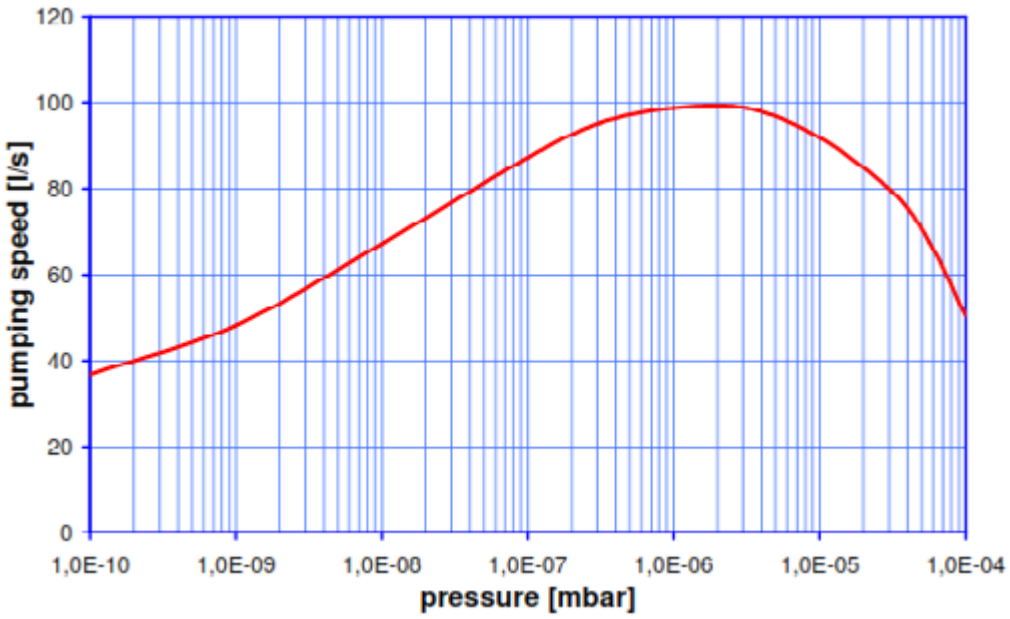
and the sputtering process stops. Maximum pumping speed occurs at about 10^{-6} mbar (see below:)

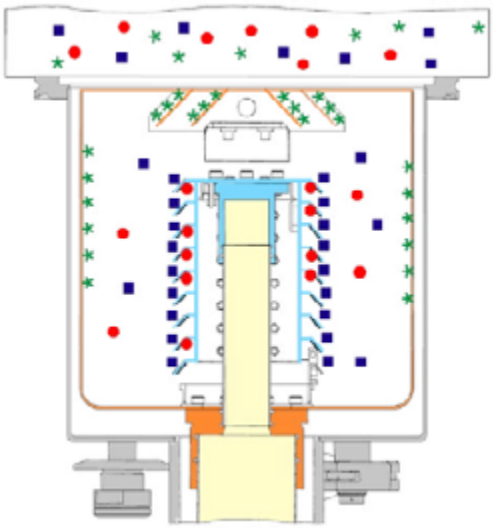


F. Cryopumps:

(Ref: Vacuumscienceworld.com)

Cryo-pumps work by condensing the gas on a cold surface, and/or adsorbing the gas on an adsorbent such as activated charcoal.

Low temperatures are obtained with a two-stage cryo-cooler, first stage being at 50 to 80 K and the second stage at about 10K:



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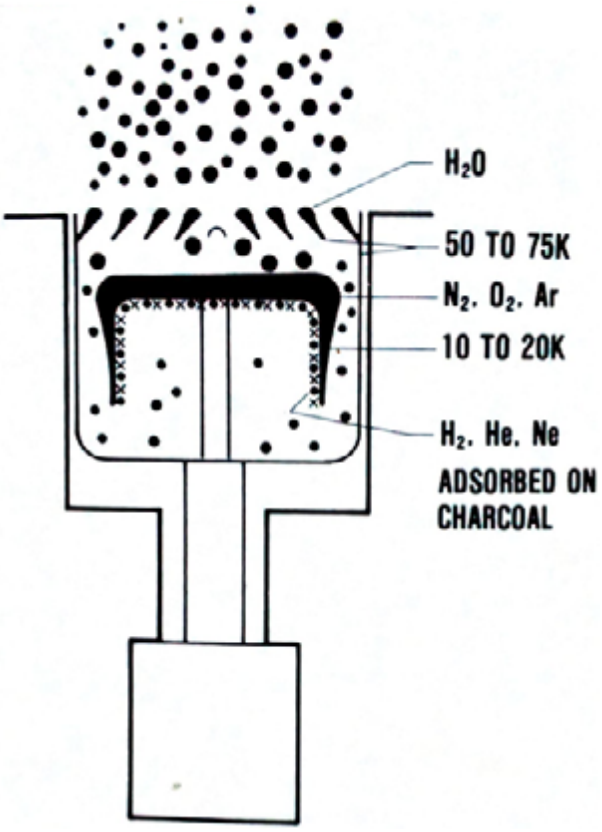
Schematic diagram of AirProducts cryopump:



First stage of cold head is connected to a thermal radiation shield, and condenses H2O and CO2. Going through the baffle, N2, O2 or Ar will condense on the second stage. H2, He and Ne are not condensed by cold heads, and are adsorbed by the adsorbent, coated on the inside of the cryopanels attached to the second stage.

Ideal pumping speed for an orifice, for different gases at 20 C, are as follows:

H2: 44.6 lit/s/cm^2

H2O: 14.9 lit/s/cm^2

N2: 11.9 lit/s/cm^2

H2O, which is condensed first at the 50K - 75K cryopanel has a net speed of 14.9 lit/s/cm^2 (same as ideal speed); however, net speed for N2 will be only about 3 lit/s/cm^2 (as compared to ideal value of 11.9 lit/s/cm^2), and for H2 the net speed will be about 5.6 lit/s/cm^2 (as compared to ideal value of 44.6 lit/s/cm^2).

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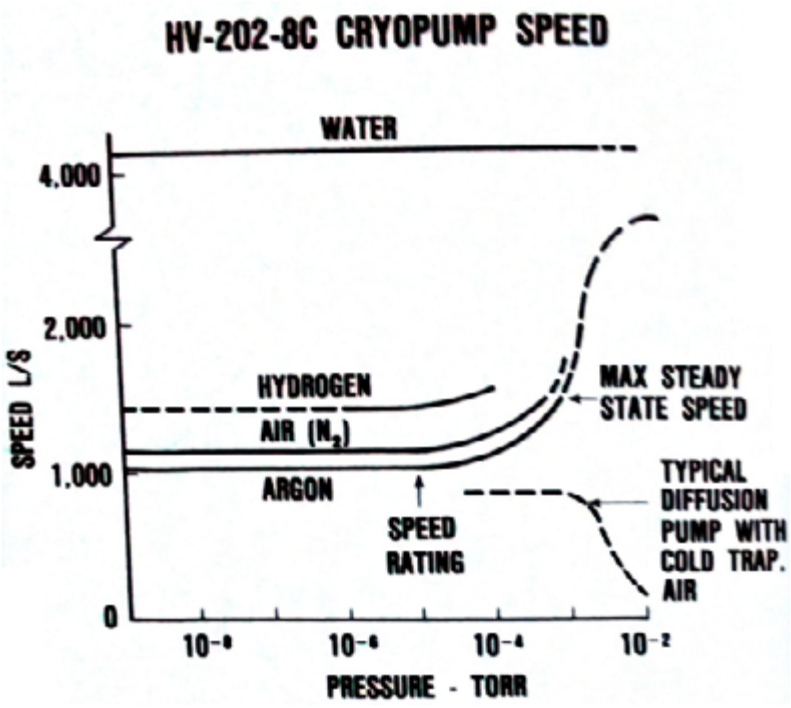
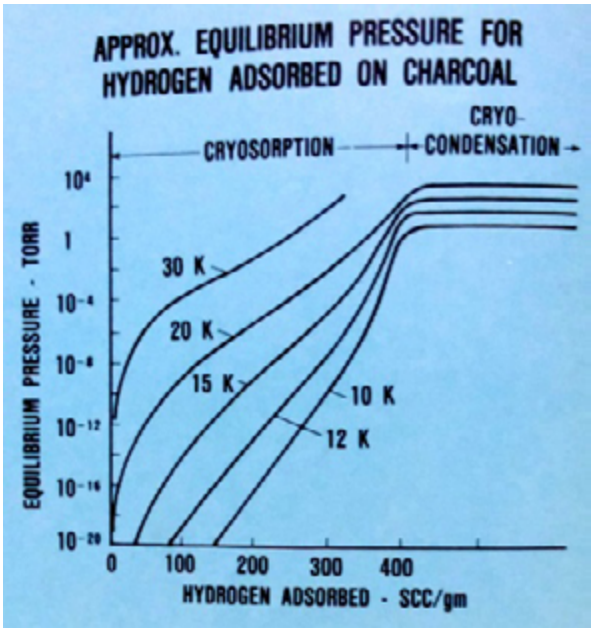
Typical pumping speeds for a particular model of Air Products cryopump are shown below: (**Ref: Basics of Cryopumping… leaflet by Air Products**)



And, for adsorption of H2 on activated charcoal, following type of graphs are available:



Cryopumps are used in ultra-high vacuum systems. A cryopump has very high pumping speed for water vapor.

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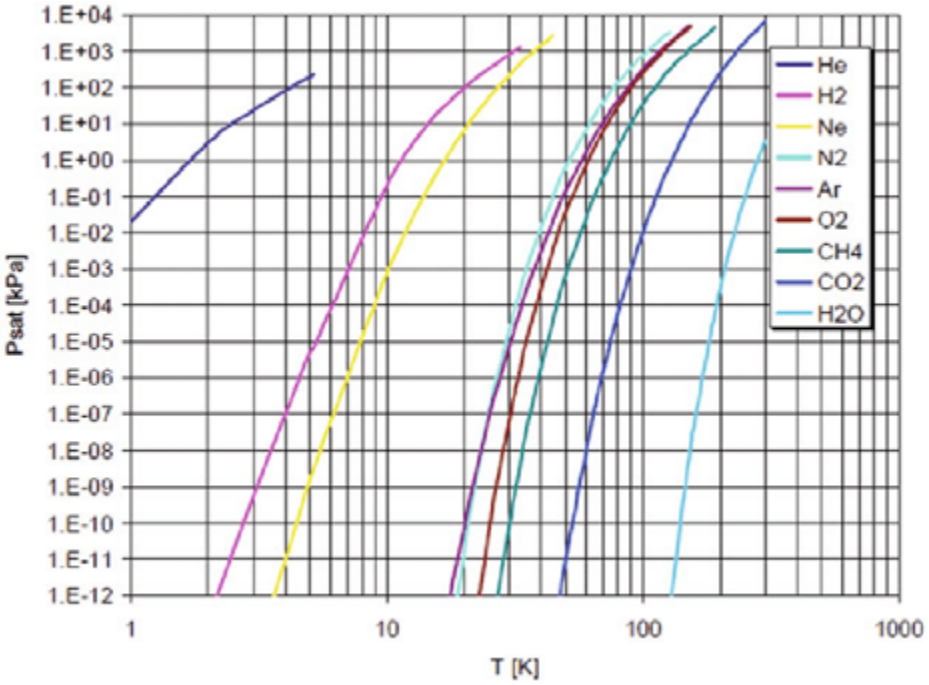
Advantages: Very low ultimate pressures, very clean vacuum, high pumping speed for H2O, no moving parts in vacuum.

Disadvantages: Lower pumping efficiency for H2, He, Ne, sensitive to heat and dust, regeneration is required, backing pump needed for start and regeneration, relatively high costs.

Vapor pressure of common gases vs temperature:



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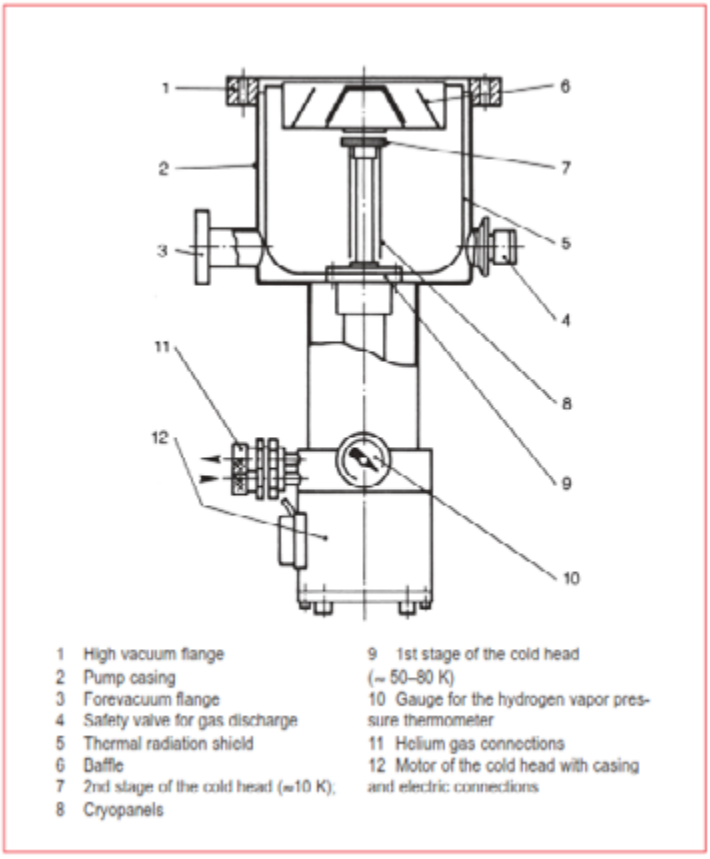
Additional data from Leybold Fundamentals:

Design of a refrigerator cryopump:



1 High vacuum flange
2 Pump casing
3 Forevacuum flange
4 Safety valve for gas discharge
5 Thermal radiation shield
6 Baffle
7 2nd stage of the cold head (≈10 K);
8 Cryopanels
9 1st stage of the cold head (≈ 50–80 K)
10 Gauge for the hydrogen vapor pressure thermometer
11 Helium gas connections
12 Motor of the cold head with casing and electric connections

Thumb-rule for cross over pressure (pc) while using a backing pump:

$$p_c \leq \left(\frac{35}{V}\right) \cdot Q2 \qquad \text{..mbar}$$

where:

V = volume of vacuum chamber (lit), and

Q2 = Net refrigerating capacity at the second stage cold head, at 20 K

Ultimate pressure (pult) obtainable for cryo-condensation is:

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$$p_{ult} = p_s(T_K) \cdot \sqrt{\frac{T_w}{T_K}}$$

where

$p_s(T_K)$ = sat. vap. pressure of gas to be pumped at temp T_K of the cryopanel (see above graphs)

T_W = temp of wall of vacuum vessel (wall temp … approx. 300 K)

Ref.[1] gives *the calculation formulas* for a cryopump:

Ultimate pressure is given by:

$$p_u = \frac{p_v}{2} \cdot \left[1 + \left(\frac{T1}{T2}\right)^{\frac{1}{2}}\right]$$

where, p_v = vapor pressure of gas at cryosurface temp.

Note that ultimate pressure is ***not*** the vapor pressure of condensate.

Thus, for a warm surface temp of 300K and cold surface temp of 20 K, we get:

$$p_u = 2.436 \cdot p_v$$

For a simple, parallel plate cryopump:

T_1 is the warm surface temp, and T_2 is the cryosurface temp.

General expression for pumping speed is:

$$\frac{S_p}{A} = \frac{\left(\frac{2 \cdot R_u \cdot T_1}{\pi \cdot M}\right)^{\frac{1}{2}} \cdot \left(1 - \frac{p_u}{p}\right) \cdot f}{1 + \left(\frac{p_u}{p}\right) \cdot \left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}} - 1\right] + G}$$

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where

$$G=(1-f)\cdot\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\cdot\left[1-\frac{p_u}{p}\cdot\left[1-\left(\frac{T_2}{T_1}\right)^{\frac{1}{2}}\right]\right]$$

For the special case of unity sticking coefficient, i.e. f = 1, we have G = 0, and we get:

$$\left(\frac{S_p}{A}\right)_{f=1}=\left(\frac{2\cdot R_u\cdot T_1}{\pi\cdot M}\right)^{\frac{1}{2}}\cdot\frac{\left(1-\frac{p_u}{p}\right)}{1+\left(\frac{p_u}{p}\right)\cdot\left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}-1\right]}$$

Selected values of sticking coeffs are given below [1]:

Gas Being Pumped	Cryosurface Temperature (K)	Warm-Surface Temperature (K)	Sticking Coefficient f	Reference
Ammonia	77.3	300	0.45	Brown and Wang 1965
Argon	20	77.3	0.79	Dawson et al. 1964
CO_2	77.3	300	0.62	Brown and Wang 1965
CO_2	20	195	0.90	Dawson et al. 1964
CO_2	77.3	195	0.80	Dawson et al. 1964
CO_2	20.2	300	0.65	Dawson et al. 1964
CO_2	77.3	300	0.63	Dawson et al. 1964
CO_2	21.0	400	0.44	Dawson et al. 1964
CO_2	77.3	400	0.49	Dawson et al. 1964
Nitrogen	20	...	0.55	Moore 1962
Nitrogen	20	85	0.73	Hurlbut and Mansfield 1963
Nitrogen	20	77.3	0.87	Dawson et al. 1964
Water	77.3	300	0.92	Brown and Wang 1965

Also, according to Brown and Wang (1965), sticking coeff for a cryopanel at 77.8 K with a warm surface temp of 300 K, is related to Mol. Wt. as follows:

$f=0.453+0.256\cdot\log(M)$ ....for M <= 137 g/mol

$f=1$ ....for M > 137 g/mol

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For more complex cryopumping arrays, instead of sticking coeff, a capture coeff (C_c) is defined as the ratio of the number of molecules captured by the array to the number of molecules that strike the array. Then, the pumping speed per unit frontal area of the array is given by:

$$\frac{S_p}{A} = \frac{C_c}{2 - C_c} \cdot \left(\frac{2 \cdot R_u \cdot T_1}{\pi \cdot M} \right)^{\frac{1}{2}} \cdot \left(1 - \frac{p_u}{p} \right)$$

where, T_1 is the temp of warm surface.

Some arrays and their capture coeffs are given below [1]:

Fig. 8.10. Cryopump arrays. (a) Plate-shielded array; (b) chevron-shielded array; (c) Santler array; (d) cryopump for high-velocity wind-tunnel cryopumping.

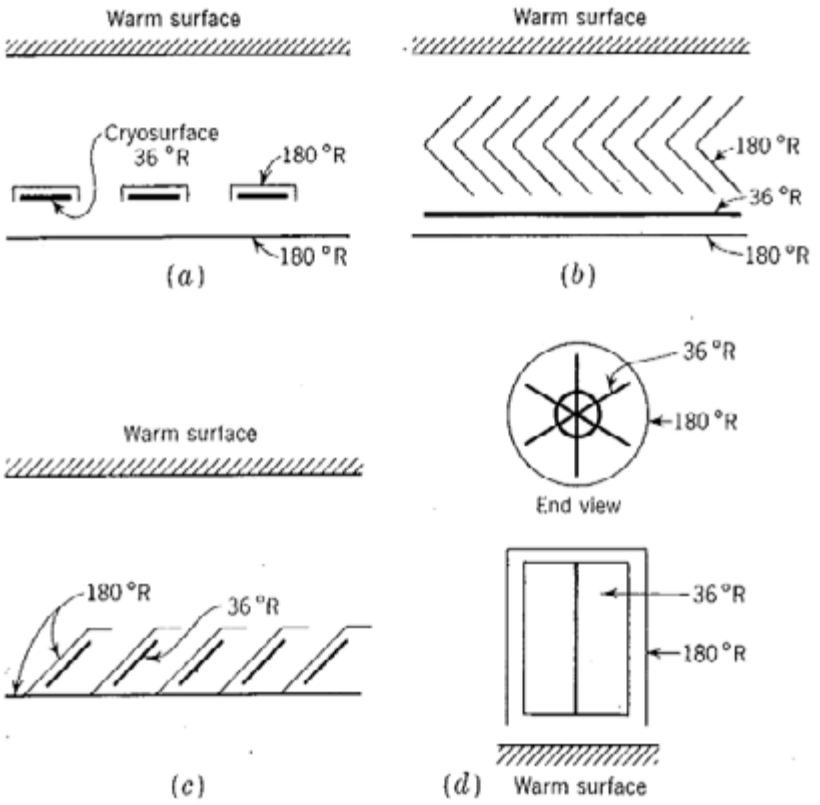

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Table 8.5. Capture coefficients C_c for various cryopump configurations when pumping air (or nitrogen)

Cryopump Configuration	Capture Coefficient C_c	Reference
Arrangement (a), Fig. 8.9	0.25	A. D. Little 1960
Arrangement (b), Fig. 8.9	0.27	A. D. Little 1960
Arrangement (c), Fig. 8.9	0.45	A. D. Little 1960
Arrangement (d), Fig. 8.9	0.79	Barnes and Hood 1962
NRC Modular Cryopump	0.26	Hoenig 1964
Air Products AP-8S	0.31	Bentley 1980

Example 7.4. A cryopump (which may be assumed to be approximated by the parallel-plate arrangement in Fig. 8.12) has the warm surface at 300 K (540°R) and the cryopanel is maintained at 20 K (36°R). The gas within the vacuum space is nitrogen, which has a vapor pressure of 6.0 nPa (4.5 x 10^{-11} torr) at 20 K. The sticking coefficient is 0.95, and the operating pressure of the system is 80 nPa (6.0 x 10^{-10} torr). A pumping speed of 25 m3/s (883 ft3/sec) is required. Determine the required cryopanel surface area.

Solution:

This is a worked-out problem in Barron [1]

Data:

$p_v := 6.0$ nPa ... vap pressure of N2 at 20 K

$T_1 := 300$ K .. warm surface temp

$T_2 := 20$ K ... cryosurface temp

$M := 28$ g/mol... mol. wt. of N2

$f := 0.95$ ....sticking coeff.

$p := 80$ ...nPa ...operating pressure

$R_u := 8314.34$ J/kg mol.K .... Universal gas const.

$S_p := 25$ m^3/s ... required pumping speed

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Then, we have: Ultimate pressure:

$$p_u := \frac{p_v}{2} \cdot \left[1 + \left(\frac{T_1}{T_2} \right)^{\frac{1}{2}} \right]$$

i.e. $p_u = 14.619$ ...nPa ... ultimate pressure

For a simple, parallel plate cryopump:

Factor G is given by:

$$G := (1 - f) \cdot \left(\frac{T_1}{T_2} \right)^{\frac{1}{2}} \cdot \left[1 - \frac{p_u}{p} \cdot \left[1 - \left(\frac{T_2}{T_1} \right)^{\frac{1}{2}} \right] \right]$$

i.e. $G = 0.1674$

Therefore, pumping speed per unit area is given by:

$$S_{p\_by\_A} := \frac{\left(\frac{2 \cdot R_u \cdot T_1}{\pi \cdot M} \right)^{\frac{1}{2}} \cdot \left(1 - \frac{p_u}{p} \right) \cdot f}{1 + \left(\frac{p_u}{p} \right) \cdot \left[\left(\frac{T_1}{T_2} \right)^{\frac{1}{2}} - 1 \right] + G}$$

i.e.

$S_{p\_by\_A} = 109.2492$ **m/s.. = (Sp / A)... pumping speed per unit area of cryosurface ..**

Therefore, required surface area is:

$$A := \frac{S_p}{S_{p\_by\_A}}$$

i.e. $A = 0.2288$ **m^2 .. required surface area .... Ans.**

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A simple Excel Worksheet to solve the above problem is shown below:

Data:			
Vap. Pr. of N2 at 20 K:	p_v	6	nPa
Warm surface temp.	T_1	300	K
Cryosurface temp.	T_2	20	K
Mol. Wt.	M	28	kg/kmol
Sticking coeff.	f	0.95	
Operating pressure	p	80	nPa
Unuversal gas const.	R_u	8314.34	J/kmol.K
Reqd pumping speed	S_p	25	m^3/s
Calculations:			
Ultimate pressure:	p_u =	14.61895	nPa
Factor G is given by:	G =	0.167399	
Numerator in S_P_byA	A_num =	184.8933	
Denominator in S_p_byA	A_denom =	1.692399	
Pumping speed per uinit area	S_p_byA =	109.2492	m/s
Required surface area	A =	0.228835	m^2 ... Ans.

$$p_u := \frac{p_v}{2}\left[1+\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\right]$$

$$G := (1-f)\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\left[1-\frac{p_u}{p}\left[1-\left(\frac{T_2}{T_1}\right)^{\frac{1}{2}}\right]\right]$$

$$S_{p\_by\_A} := \frac{\left(\frac{2R_uT_1}{\pi \cdot M}\right)^{\frac{1}{2}} \cdot \left(1-\frac{p_u}{p}\right) \cdot f}{1+\left(\frac{p_u}{p}\right) \cdot \left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}-1\right]+G}$$

Application:

(Ref: Thermal system of a 3.0 m dia, 3.5 m long Thermovac chamber by M. Thirumaleshwar, 12th Intl. Cryogenic Engineering Conference, Southampton, England, 12-15 July, 1988).

Details of a 3.0 m dia x 3.5 m long Thermovac chamber, installed for Indian Space Research Organization (ISRO), Bangalore, India, are given below:

Abstract:

A 3.0 m dia x 3.5 m long Thermovacuum Chamber (TVC) has been designed, fabricated and installed for Indian Space Research Organization (ISRO). This chamber is used for testing the components/sub-systems of Indian Remote Sensing (IRS), INSAT-II and GMS (Geostationary Meteorological Satellite) series satellites. Cryogenic Thermal System of this chamber is described. Results obtained during trial runs are also presented

Specifications:

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Payloads of the IRS and INSAT-II series have to be space qualified by Thermovacuum tests. For doing this, a 3.0 m dia x 3.5 m long TVC is designed and fabricated (Fig.1).

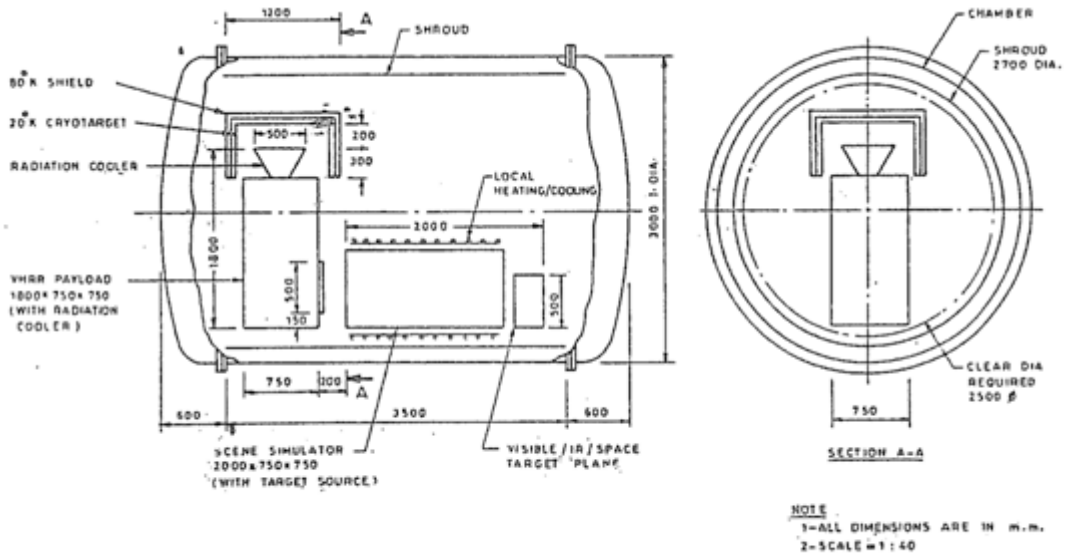

Fig. 1 Schematic of 3 m dia Thermovac chamber

General specification of the chamber is as follows:

1. Size: 3.0 m dia x 3.5 m long
2. Pressure: Better than 10^{-5} torr, within 5 hrs. (clean, oil free vacuum is required)
3. Temperature:

Main shroud:

a. 173K to 373K. continuously variable when the package power dissipation is 150 W;
b. 100K when the package power dissipation is l kW;
c. Extreme temperatures to be obtained within 6 hrs., starting from ambient.

Scene Simulator Shroud: 298K +- 5K

Cryotarget and Radiation cooler: 20K

Major payloads to be tested are Linear Imaging Self Scan (LISS) Cameras of IRS-1, communication transponder of INSAT-II, Very High Resolution Radiometer (VHRR) of INSAT type, Synthetic Aperture Radar(SAR) and VHRR of GMS type. Thermal system requirements are given in Table 1:

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TABLE 1

3.0m dia TVC - Thermal System requirements

Payload	Max. power Dissipation(W)	Shroud Temp. (K)
IRS-LISS	40	173-373
VHRR (INSAT)	80	173-373
VHRR (GMS)*	100	173-373
PROTO INSAT	1000	100-373
SAR	1000	100-373

* Radiation cooler and space target to be cooled to 20K

Scene simulator which simulates targets at infinity for the payload, is located very close to the payload in the vacuum chamber to prevent the effects due to temperature gradient.

Desired clean vacuum is obtained by a vacuum system consisting of two nos. Rotary Mechanical Pumps (300 cfm and 140 cfm speed), Two Roots Vacuum pumps (600 1/s each). one Turbomolecular pump (2000 1/s speed) and two Cryopumps (each of 10,000 1/s speed for Nitrogen).

Thermal system:

Fig.2 shows a schematic diagram of the Thermal system:

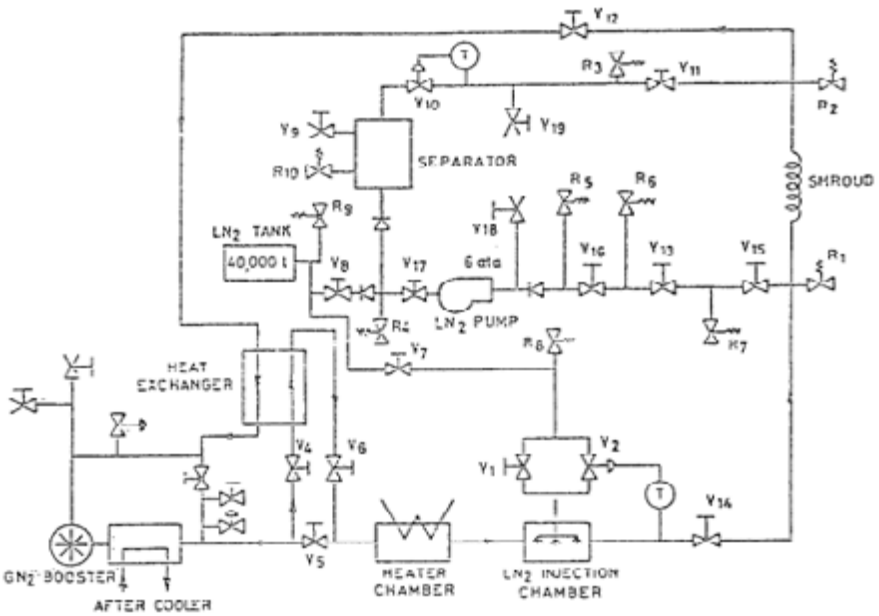

Fig. 2 Thermal system

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Desired temperatures are obtained by surrounding the payload by a Thermal shroud and by cooling/heating of this shroud. Shroud is constructed by arranging extruded copper tube-fin sections (20 mm i.d.) in a Chevron array. Inside surface of the Shroud is coated black with a "space quality" paint. Outside surface of the shroud and inside surface of the vacuum chamber are given bright-finish to reduce radiation loss. During 'cold cycle' (173K to 300K), a GN2 blower circulates GN2 through the shroud at a pressure of 3 ata. Desired temperature is obtained by injecting LN2 into this stream. During 'hot cycle' (300 K - 373K), desired temperature is obtained by heating the GN2 stream by electrical heaters (12 kW).

To obtain temperature of 100 K, sub-cooled LN2 is circulated at a pressure of 6 ata by a centrifugal pump (2500 1/h). The shroud (cylindrical + end shrouds) is made of many parallel paths. These sections are connected in parallel during GN2 flow and in series for LN2 flow. This is achieved by suitable valving arranged outside the vacuum chamber.

The scene simulator shroud is also made of copper tube-fin sections. During 'hot cycle', this shroud is cooled by a mechanical refrigeration unit (2 Ton capacity). During cold cycle it is heated by the hot brine (3 KW heaters). Various heat loads on the shroud are shown in Table 2.

TABLE 2

Heat loads for 3.0m dia TVC

Load (W)	Temperature (K)		
	100	173	373
Radiation	1900	1700	2650
Conduction	200	200	300
Dissipation	1000	100	
Scene Simulator		250	200
Total -	3100	2250	3150

20 K target and radiation cooler are designed to be cooled by a Stirling cycle cryogenerator. Thermal shroud has approximately 700m length of finned tubing and weighs about 3300 kg.

Heat transfer and pressure drop data for the shroud are given in Table 3.

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TABLE 3

3.0 m dia TVC - Heat Transfer & Pressure Drop in Shroud

Parameter	Symbol	Temperature(K)		
		100	173	373
Reynold's No.	Re(x 10^4)	1.2	10.9	5.95
Velocity	(m/s)	0.08	10	22
Pr. drop	ΔP (psi)	0.05	2.5	4.6
Heat tr. coeff	h($W/m^2.K$)	325	175	215

Results:

During the trial runs following results were obtained:

1. Pull up time to 373K: 6 hrs (satisfactory)
2. Pull down time to 173K: 5 hrs (satisfactory)
3. Consumption of LN2:

   for

   a. pre-cooling : 2600 l
   b. at 173K: 180 1/h
   c. Uniformity of temp. on shroud : (+ or -) 2.5 C
   d. Temp. control : (+ or -) 1 C

4. Successful trials have been conducted at 100K recently.

[**Further References** on this topic of Thermovacuum chambers for ISRO:

1. Thirumaleshwar, M. 'Design of a thermal system for Thermovacuum Chambers'. Cryogenics, vol. 18 (1978), pp 607-613 **[..See Appendix-2 for full paper**]
2. Thirumaleshwar, M., Vyawahare, M.R. and Pravin Kumar, M. 'Design aspect of the Thermal System of a Thermovacuum Chamber'. Cryogenics, vol. 22 (1982), pp 649-652]

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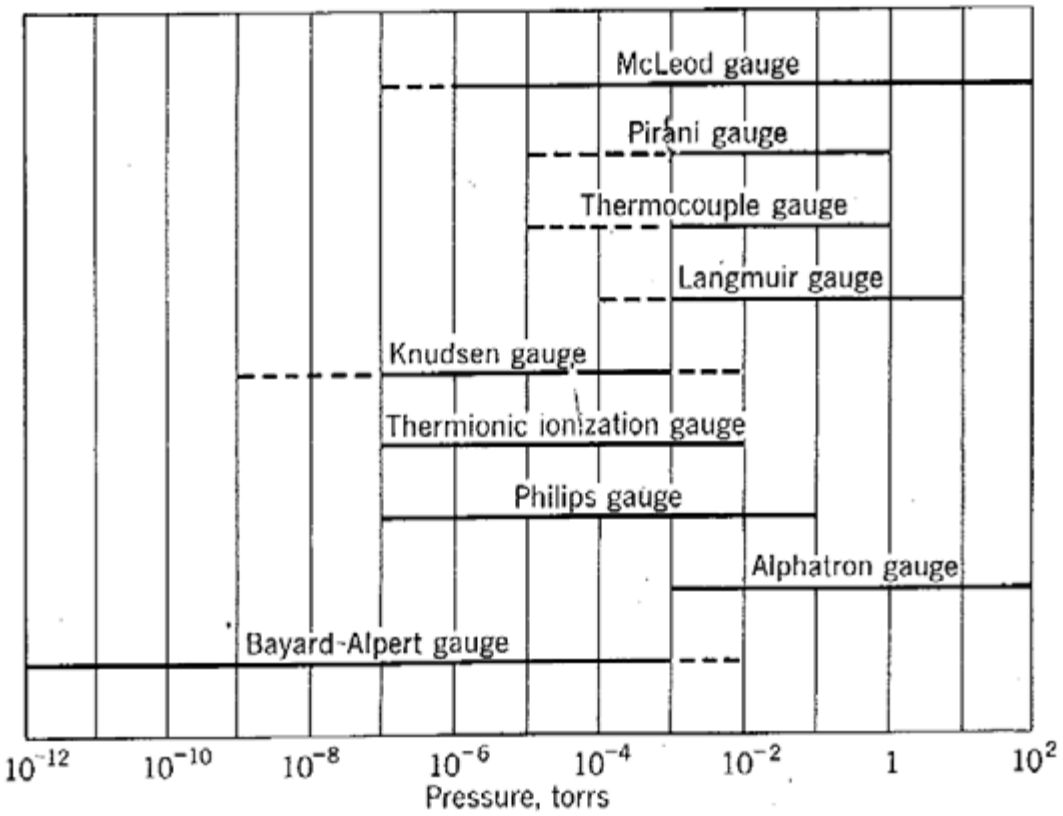
7.7.3 MEASUREMENT OF VACUUM

Some of the vacuum gauges used are [1]:

1. McLeod gauge (isothermal compression)
2. Thermal conductivity gauge (Pirani and thermocouple gauges)
3. Viscosity gauge (Langmuir gauge)
4. Radiometer gauge (Knudsen gauge)
5. Ionization gauges (thermionic, Philips, Alphatron, Bayard-Alpert and Penning gauges)

Operating range for various vacuum gauges [1]:



We will discuss Thermal conductivity gauges and Ionization gauges only, since they are most used in practice:

A. The thermocouple gauge[1]:

Its principle is: heat-transfer rate in free-molecular conduction is proportional to the absolute pressure of the gas, if radiation effects are cancelled.

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Here, the filament is heated with a constant input, and the equilibrium temperature of the filament (as measured by a thermocouple) gives a measure of the vacuum pressure within the gauge.

Ref: www.idealvac.com:

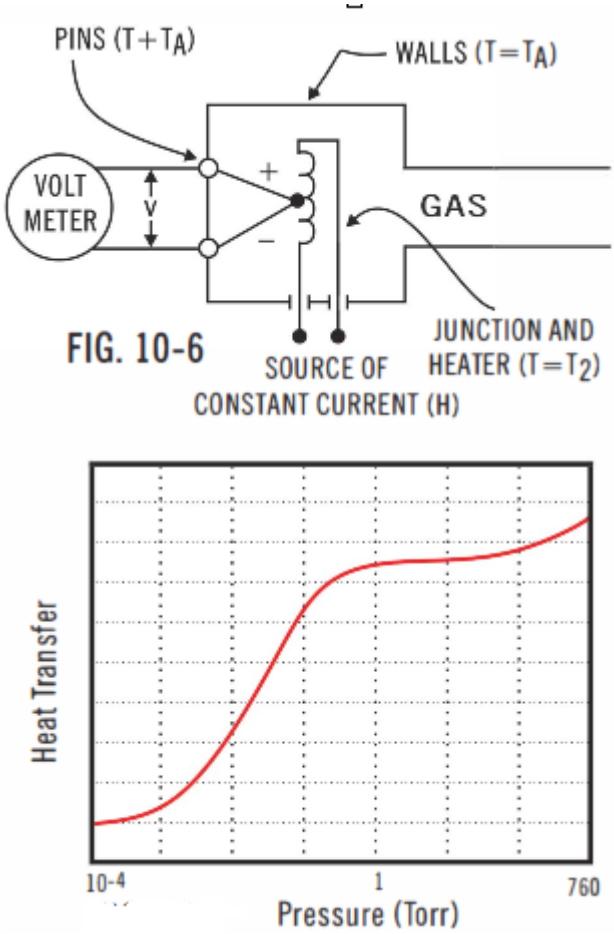

FIG. 10-6

B. Pirani gauge (Pirani 1906) [1]: Its principle is the same as for thermocouple gauge, viz. heat-transfer rate in free-molecular conduction is proportional to the absolute pressure of the gas, if radiation effects are cancelled.

Ref: www.idealvac.com:

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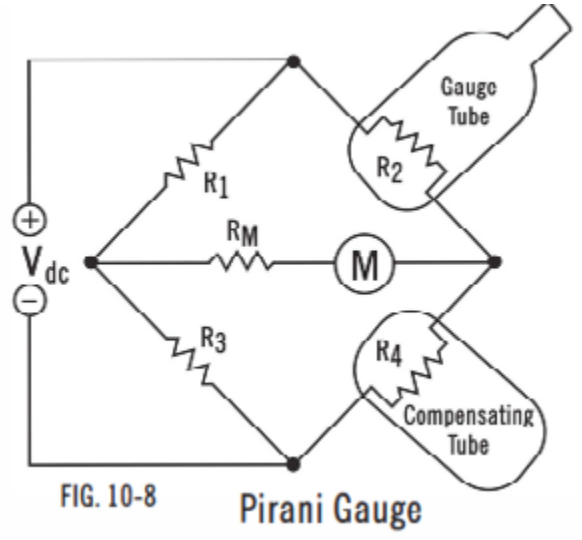

FIG. 10-8 Pirani Gauge

C. The thermionic or hot-cathode ionization gauge[1]:

It works on the principle:

Fast-moving electrons passing through a gas ionize some of the gas molecules. For a constant current of electrons at a given velocity, the rate at which ions are formed is proportional to the number of gas molecules per unit volume, which in turn is proportional to the gas pressure for pressures below about 100 mPa (or about 10^{-3} torr).

Ref: www.idealvac.com:

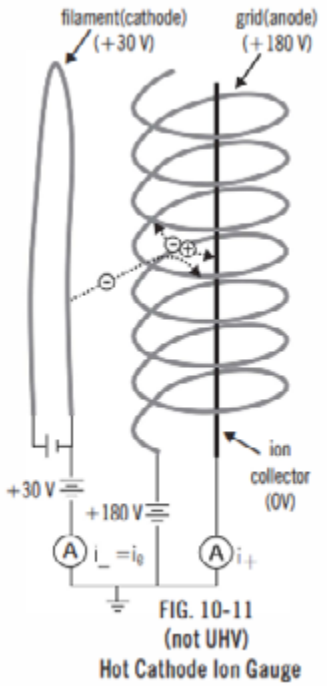

FIG. 10-11
(not UHV)
Hot Cathode Ion Gauge

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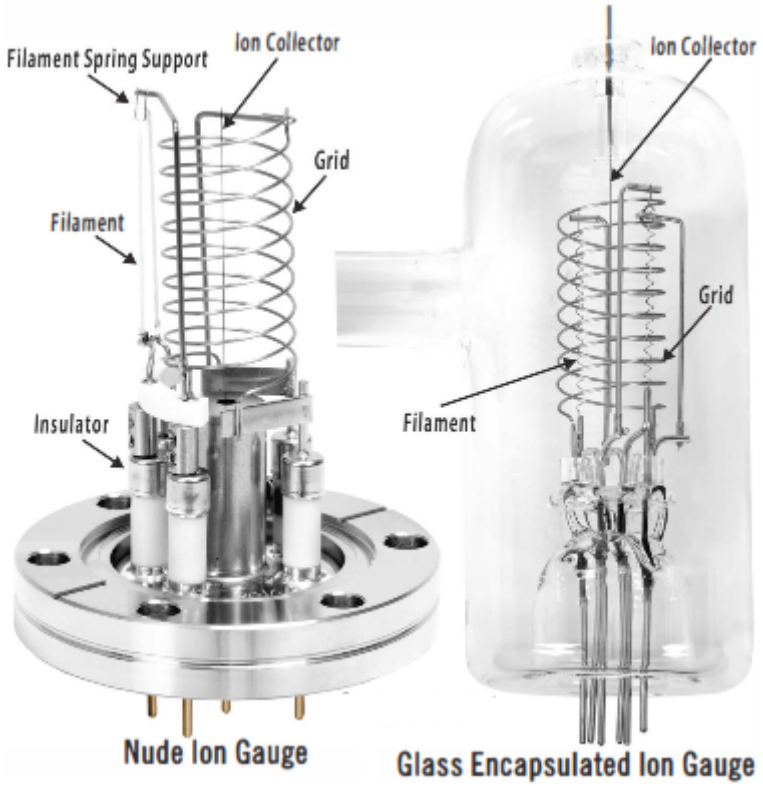
The thermionic vacuum gauge is limited to pressures above about 1 μPa (about 10^{-8} torr) by the X-ray effect.

D. Bayard and Alpert (1960) gauge [1]:

Here, X-ray effect was overcome by inverting the structure of the conventional ionization gauge; then, the collector intercepts only small fractions of the X-rays produced at the grid.

Ref: www.idealvac.com:



With this arrangement, the useful range of the gauge is extended to about 10 nPa (about $l0^{-10}$ torr).

Ideal Vacuum Products (Ref: www.idealvac.com) gives a Vacuum Reference chart and also a good summary of vacuum gauges:

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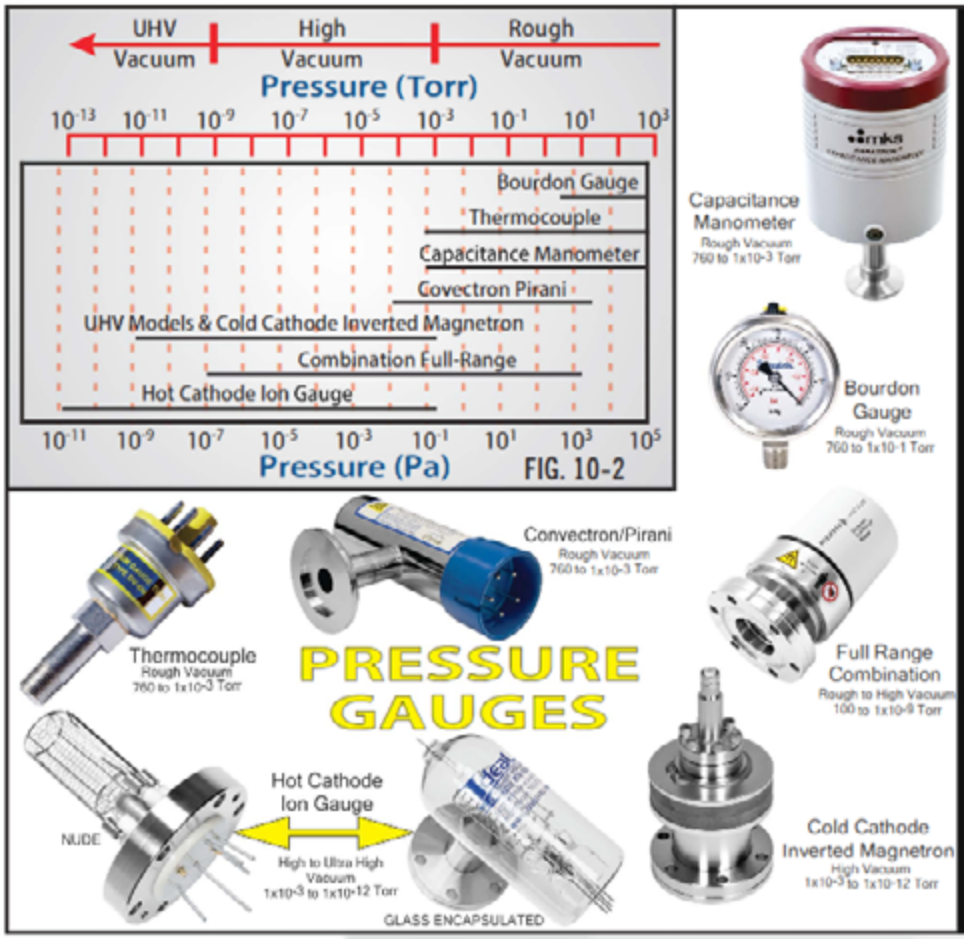
Vacuum Reference Chart

Torr	mm Hg Absolute	Feet	Miles	Meters	in Hg Vacuum	in Hg Absolute	PSIA	Pa	Bar	atm
0.0075	0.0075	656,000	124.3	200,000	29.919	9.43X10-8	4.64X10-8	0	0.00001	0.00
1.09	1.09	150,000	28.4	45,720	29.877	0.04	0.02	150	0.00146	0.00
8	8	100,000	18.9	30,510	29.591	0.33	0.16	1120	0.01067	0.01
13	13	90,000	17.1	27,459	29.4	0.52	0.26	1760	0.01733	0.02
34	34	70,000	13.3	21,357	28.595	1.33	0.65	4490	0.04533	0.04
54	54	60,000	11.4	18,306	27.785	2.14	1.05	7240	0.07199	0.07
69	69	55,000	10.4	16,781	27.208	2.71	1.33	9170	0.09199	0.09
87	87	50,000	9.5	15,255	26.476	3.44	1.69	11650	0.11599	0.11
111	111	45,000	8.5	13,730	25.545	4.38	2.15	14820	0.14799	0.15
141	141	40,000	7.6	12,204	24.362	5.56	2.73	18820	0.18798	0.19
179	179	35,000	6.6	10,679	22.86	7.06	3.47	23930	0.23865	0.24
226	226	30,000	5.7	9153	21.017	8.90	4.37	30130	0.30131	0.30
282	282	25,000	4.7	7628	18.8	11.12	5.46	37650	0.37597	0.37
350	350	20,000	3.8	6102	16.16	13.76	6.76	46610	0.46663	0.46
429	429	15,000	2.8	4577	13.03	16.89	8.29	57160	0.57195	0.56
522	522	10,000	1.9	3050	9.34	20.58	10.10	69640	0.69594	0.69
543	543	9000	1.7	2746	8.53	21.39	10.50	72400	0.72394	0.71
564	564	8000	1.5	2441	7.69	22.23	10.91	75220	0.75194	0.74
586	586	7000	1.3	2136	6.82	23.10	11.34	78190	0.78127	0.77
609	609	6000	1.1	1831	5.93	23.99	11.78	81220	0.81193	0.80
633	633	5000	0.95	1526	5.02	24.90	12.23	84330	0.84393	0.83
644	644	4500	0.86	1373	4.55	25.37	12.46	85910	0.85859	0.85
656	656	4000	0.76	1220	4.08	25.84	12.69	87490	0.87459	0.86
669	669	3500	0.66	1068	3.59	26.33	12.93	89150	0.89192	0.88
681	681	3000	0.57	915	3.1	26.82	13.17	90810	0.90792	0.90
694	694	2500	0.47	763	2.6	27.32	13.41	92460	0.92525	0.94
706	706	2000	0.38	610	2.1	27.82	13.66	94190	0.94125	0.93
719	719	1500	0.28	458	1.59	28.33	13.91	95910	0.95859	0.95
732	732	1000	0.19	305	1.06	28.86	14.16	97630	0.97592	0.96
746	746	500	0.09	153	0.54	29.38	14.43	99490	0.99458	0.98
760	760	0	Sea Level	0	0	29.92	14.70	101330	1.01325	1.00



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7.8 PROBLEMS

Prob7.1. Determine the flow regime (continuum, transition, or free molecular) for helium gas at 30 K (54°R) and 10 Pa (0.075 torr) flowing in a 25 mm ID circular tube. For the same temperature and tube diameter, determine the minimum pressure for which continuum flow will exist. If the helium gas velocity is 30 m/s (98.4 ft/sec), determine the maximum pressure for laminar flow to exist in the 25 mm diameter tube at 30 K.[1]

Solution:

Data:
case 1:

$T := 30$ K $\quad p := 10$ Pa $\quad d := 0.025$ m

$R_u := 8314.34$ J/kgmol.K $\quad M := 4.003$ kg/kmol ... for Helium

We get:

Viscosity at 30 K: $\mu := 4.6056 \cdot 10^{-6}$ Pa-s ... from NIST ..Ref: https://webbook.nist.gov/chemistry/fluid/

See below:

Isobaric Data for P = 1.0000e-05 MPa

Temperature (K)	Pressure (MPa)	Density (kg/m3)	Volume (m3/kg)	Internal Energy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (J/g*K)	Cv (J/g*K)	Cp (J/g*K)	Sound Spd. (m/s)	Joule-Thomson (K/MPa)	Viscosity (uPa*s)	Therm. Cond. (W/m*K)	Phase
28.000	1.0000e-05	0.00017193	5816.2	92.454	150.62	34.843	3.1158	5.1931	311.35	0.42056	4.4075	0.032188	vapor
29.000	1.0000e-05	0.00016600	6024.0	95.570	155.81	35.025	3.1158	5.1931	316.86	0.36770	4.5073	0.032907	vapor
30.000	1.0000e-05	0.00016047	6231.7	98.686	161.00	35.201	3.1158	5.1931	322.28	0.31658	4.6056	0.033618	vapor
31.000	1.0000e-05	0.00015529	6439.4	101.80	166.20	35.371	3.1158	5.1931	327.60	0.27286	4.7024	0.034321	vapor
32.000	1.0000e-05	0.00015044	6647.1	104.92	171.39	35.536	3.1158	5.1931	332.84	0.23021	4.7979	0.035016	vapor

Ref: https://webbook.nist.gov/chemistry/fluid/

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Mean free path: $\lambda := \left(\frac{\mu}{p}\right) \cdot \left[\pi \cdot R_u \cdot \frac{T}{(2 \cdot M)}\right]^{\frac{1}{2}}$

i.e. $\lambda = 1.4409 \cdot 10^{-4}$ m

Knudsen Number: $K_n := \frac{\lambda}{d}$

i.e. $K_n = 5.7635 \cdot 10^{-3}$

Note: Knudsen number < 0.01 .... Therefore, continuum flow ... Ans.

2. Minimum pressure for which continuum flow will exist, for the same temp and tube dia:

i.e. what is the pressure when Kn = 0.01

$p := 1$ Pa ... guess value of pressure

Given

$$0.01 = \left(\frac{\mu}{p \cdot d}\right) \cdot \left[\pi \cdot R_u \cdot \frac{T}{(2 \cdot M)}\right]^{\frac{1}{2}}$$

pressure := Find(p)

i.e. pressure = 5.7635 Pa

i.e. Min pressure for which continuum flow will exist is: 5.7635 Pa .... Ans.

3. If the helium flow vel = 30 m/s, find max pressure for laminar flow to exist in 25 mm dia tube at 30 K:

For laminar flow, Reynolds Number is < 2300

$Re = \frac{d \cdot v \cdot \rho}{\mu}$ where, d = dia, v = vel, ρ = density, μ = visc

We have for Helium at 30 K:

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$\mu := 4.6056 \cdot 10^{-6}$ Pa-s ... from NIST ..Ref:
https://webbook.nist.gov/chemistry/fluid/

$v := 30$ m/s

$d := 0.025$ m

Therefore, to find the pressure, first, find ρ:

$$\rho := \frac{2300 \cdot \mu}{d \cdot v} \quad \text{i.e.} \quad \rho = 0.0141 \quad \text{kg/m^3}$$

i.e. ρ, density for laminar flow is: 0.0141 kg/m^3

Now, find the pressure at which density will equal this value at 30 K :

From Ideal gas law:

$p = \rho \cdot R \cdot T$ where R = Gas const for Helium

$$R := \frac{8314.34}{4.993} \quad \text{i.e.} \quad R = 1.6652 \cdot 10^{3} \quad \text{J/kg.K .. for helium}$$

Therefore:

$p := \rho \cdot R \cdot T$

i.e. $p = 705.5702$ **Pa....max pressure for laminar flow to exist in tube, at 30 K for helium .... Ans.**

Prob.7.2. Determine the throughput and mass flow rate of air at 275 K (496°R) through a piping system made up of 300 mm of 50 mm ID tubing in series with 600 mm of 25 mm ID tubing. At one end of the 50 mm line is a large vessel having an internal pressure of 250 mPa (1.875 x 10^{-3} torr), and at the other end of the 25 mm tube is a vacuum pump having an inlet pressure of 25 mPa (1.875 x 10^{-4} torr). What is the speed of the pump? [1]

Solution:

Data:

For air at 275 K, we have:

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$T := 275$ K

$\mu := 17.23 \cdot 10^{-6}$ Pa ... from Ref[1]

$R_u := 8314.34$ J/kg.K

$M := 28.97$ kJ/kmol

$p := 0.25$ Pa

$D := 0.05$ m

Now, write two Functions for mean free path and Knudsen number:

$$\lambda(p,\mu,T,M) := \frac{\mu}{p} \cdot \left(\frac{\pi \cdot 8314.34 \cdot T}{2 \cdot M}\right)^{\frac{1}{2}}$$ ....Function for Mean free path

$$Kn(p,\mu,T,M,D) := \frac{\lambda(p,\mu,T,M)}{D}$$ ....Function for Knudsen Number

In the above Functions: μ = dyn. visc in Pa-s; p = pressure, Pa; T = temp, K; M = Mol. wt, kg/kmol; Universal gas const, Ru = 8314.34 J/kmol.K; D = Diameter of tube, m

Then, we have:

$\lambda(p,\mu,T,M) = 0.0243$ m .... mean free path at a pressure of p = 0.25 Pa

$Kn(p,\mu,T,M,D) = 0.4853$ ...Knudsen number = λ/D

i.e. Kn > 0.3

Therefore, it is Free mol. flow in the 50 mm dia tube.

Conductance of 50mm dia, 500 mm long tube:

L/D = 6 (since L = 300 mm).

So, we use the eqn :

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$$C2 := \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}} \cdot \left(\frac{D^2}{10 + \frac{4}{3}}\right) \qquad \text{i.e.} \quad C2 = 0.02589 \quad \text{m^3/s}$$

i.e. $C2 := 25.89$ lit/s

Similarly for 25 mm tube of 600 mm length, conductance is determined from info given in Table 8.1 of Ref [1]:

$D1 := 0.025$ m $\quad L1 := 0.6$ m $\quad D2 := 0.05$ m

$$C1 := \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}} \cdot \left[\frac{D1^2}{\frac{L1}{D1} + \frac{4}{3} \cdot \left(1 - \frac{D1^2}{D2^2}\right)}\right]$$

i.e. $C1 = 2.9342 \cdot 10^{-3}$ m^3/s

i.e. $C1 := 2.9342$ lit/s

Then, overall conductance of these two tubes in series is:

$$C_o := \left(\frac{1}{C2} + \frac{1}{C1}\right)^{-1} \qquad \text{i.e.} \quad C_o = 2.6355 \quad \text{lit/s}$$

Then, throughput:

$Q = C_o \cdot \Delta p$

i.e. $Q := C_o \cdot (0.25 - 0.025)$

i.e. $Q = 0.59299$ Pa.lit/s

i.e. $Q := 0.59299 \cdot 10^{-3}$ **Pa-m^3/s....Ans.**

This Q corresponds to a mass flow rate of:

$$m\_dot := \frac{Q \cdot M}{R_u \cdot T} \qquad \text{i.e.} \quad m\_dot = 7.5134 \cdot 10^{-9} \text{ kg/s} \quad = 7.5134 \quad \textbf{µg/s....Ans.}$$

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Therefore, pumping speed of the pump is given by:

Remember: Throughput is the same throughout every where in the system.

At pump inlet, by data: p = 0.025 Pa; And, Throughput, Q = 0.59299 Pa-lit/s

Then:

$$S_p := \frac{0.59299}{0.025}$$

i.e. $S_p = 23.7196$ **lit/s .... pumping speed of pump... Ans.**

Prob.7.3. Determine the pump-down time required to evacuate a leak-free space containing 0.750 m3 (26.5 ft3) of air initially at 2.0 Pa (0.015 torr) and 300 K (540°R). The space is to be evacuated to a final pressure of 40 mPa (3.0 x 10^{-4} torr) through a 25 mm ID tube having a length of 1.50 m. The vacuum pump speed is constant at 5 dm3/s.[1]

Solution:

Data:

$S_p := 5$ lit/s ..... pump speed

$d := 0.025$ m .... ID of the tube

$L := 1.5$ m .... length of tube

$p_1 := 2$ Pa ... initial pressure

$p_2 := 0.04$ Pa ... final pressure

$V := 0.75$ m^3 ... volume to be pumped

Pump down time is determined from:

$$S_s = \left(\frac{V}{t_p}\right) \cdot \ln\left(\frac{p_1}{p_2}\right)$$

where Ss = system pumping speed, t_p = pump down time

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System pumping speed (Ss) is related to pump speed (Sp) as:

$$\frac{1}{S_s}=\frac{1}{S_p}+\frac{1}{C_o}$$ where Co = total conductance between pump and the chamber

Conductance of the tube:

$p\_bar := \frac{p_1 + p_2}{2}$ i.e. $p\_bar = 1.02$ Pa....mean pressure

$d := 2.5$ cm

Note: 1 mbar = 100 Pa ... Therefore:

$d \cdot p\_bar \cdot 10^{-2} = 0.0255$ mbar.cm

Thus: d.p_bar >0.01 and <0.6 , i.e. flow regime is: transition flow.

Then, conductance of tube for air at 20 C, is given by:

$$C\_o := 135 \cdot \frac{d^4}{L} \cdot p\_bar + 12.1 \cdot \frac{d^3}{L} \cdot \frac{1 + 192 \cdot d \cdot p\_bar}{1 + 237 \cdot d \cdot p\_bar}$$ lit/s

where:

$d := 2.5$ cm $L := 150$ cm $p\_bar := 1.02 \cdot 10^{-2}$ mbar

i.e. $C\_o = 1.4137$ lit/s

Therefore, system pumping speed, Ss:

$S_s := \left(\frac{1}{S_p} + \frac{1}{C_o}\right)^{-1}$ i.e. $S_s = 1.7258$ lit/s

Therefore, pump down time:

$p_1 = 2$ Pa $p_2 = 0.04$ Pa $V = 0.75$ m^3

$$t_p := \left(\frac{V \cdot 1000}{S_s}\right) \cdot \ln\left(\frac{p_1}{p_2}\right)$$ sec

i.e. $t_p = 1.7001 \cdot 10^3$ **sec = 28.34 min ... Ans.**

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Prob.7.4. The annular space of a liquid oxygen storage vessel is to be pumped down from an initial pressure of 10 kPa to a final pressure of 10 Pa. The Volume of the annular space is 50 m3, and the overall conductance of the piping system is 80 dm3/s. The ultimate pressure of the system is 2 Pa, and the desired pump-down time is 3 hours. Determine the required pumping speed (assumed constant) for the vacuum pump. [1]

Solution:

We have: $S_s = \left(\frac{V}{t_p}\right) \cdot \ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$

Data:

$V := 50$ m^3 $t_p := 10800$ sec $p_1 := 10000$ Pa $p_2 := 10$ Pa

$p_u := 2$ Pa $C_o := 80$ lit/s.... overall conductance

Then:

$$S_s := \left(\frac{V}{t_p}\right) \cdot \ln\left(\frac{p_1 - p_u}{p_2 - p_u}\right)$$

i.e. $S_s = 0.033$ m^3/s = 33 lit/s

Then, required pump speed is found from:

$$\frac{1}{S_p} = \frac{1}{S_s} - \frac{1}{C_o}$$

i.e. $S_p := \left(\frac{1}{33} - \frac{1}{80}\right)^{-1}$ lit/s

i.e. $S_p = 56.1702$ **lit/s .... Ans.**

To be safe, choose a pump with a pumping speed of 60 or 70 lit/s

---

Prob.7.5. A vacuum vessel is initially filled with air at 100 kPa and 300 K. The vessel volume is 0.850 m3, and the desired final pressure is 100 mPa. The system pumping speed

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is constant at 5 dm3/s. Determine: (a) the pump-down time, assuming no inleaks present; (b) the pump-down time if an inleak of 0.10 mPa-m3/s is present; and (c) the maximum inleak rate if the ultimate pressure for the system is to be 100 mPa. [1]

Solution:

Data:

$p1 := 100000$ Pa $T1 := 300$ K $V := 850$ lit $p2 := 0.1$ Pa

$S_s := 5$ lit/s $Q_i := 10^{-4}$ Pa-m^3/s $p_u := 0.1$ Pa

Case 1: pump down time with no inleaks:

$$t_p := \left(\frac{V}{S_s}\right)\cdot\ln\left(\frac{p1}{p2}\right)$$

i.e. $t_p = 2.3486\cdot10^3$ **sec = 39.14 min .... Ans.**

Case 2: pump down time with an inleak of Qi:

When Qi is present, ultimate pressure will be:

$$p2\_ult := \frac{Q_i\cdot1000}{S_s}$$

i.e. $p2\_ult = 0.02$ Pa

Then, pumpdown time is given by:

$$t_{p2} := \left(\frac{V}{S_s}\right)\cdot\ln\left(\frac{p1 - p2\_ult}{p2 - p2\_ult}\right)$$

i.e. $t_{p2} = 2.3866\cdot10^3$ **sec = 39.78 min.... Ans.**

Case 3: Max inleak rate if if the ultimate pressure is 0.1 Pa:

$p_u = 0.1$ Pa

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i.e. $p_u = \frac{Q_{i3} \cdot 1000}{S_s}$ where Qi3 = max inleak rate in Pa-m3/s

i.e. $Q_{i3} := \frac{p_u \cdot S_s}{1000}$

i.e. $Q_{i3} = 5 \cdot 10^{-4}$ **Pa-m^3/s .... Ans.**

Prob.7.6. In the vacuum system shown in Fig. 8.21, the pressure in the manifold above the pump is 60 mPa (4.5 x 10^{-4} torr), and the pressure in the evacuated space is 120 mPa (9.0 x 10^{-4} torr). The temperature throughout the system is 39°C (312.2 K), and the gas flowing through the system is air (viscosity = 19.07 μPa-s). In the upper tube, a small leak of 25 mPa-m3/s is present. The conductance of the left part of the upper tube is 110 dm3/s, and the conductance of the right part of the upper tube is 55 dm3/s. The lower tube is 500 mm long and has an ID of 50 mm. Determine the total throughput through the pump.[1]

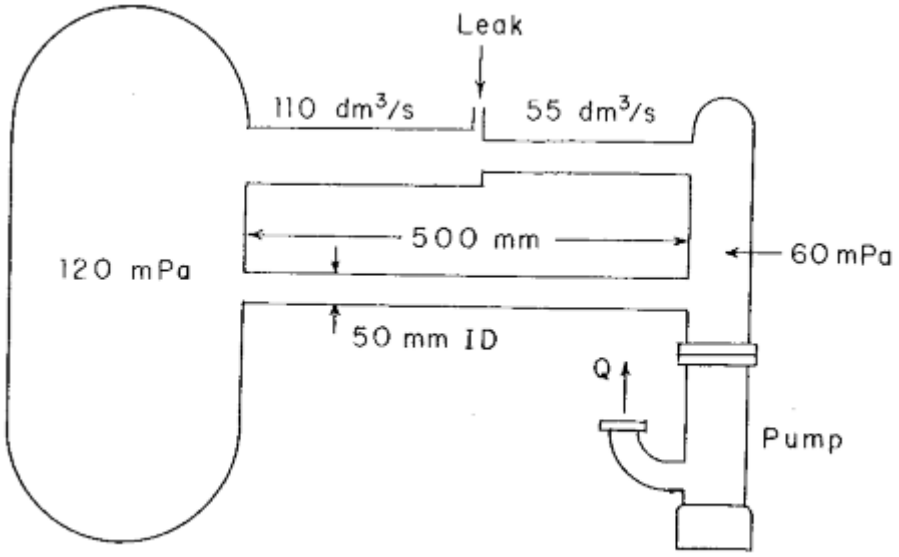

Fig. 8.21.

Solution:

Data:

$p_1 := 0.12$ Pa $p_2 := 0.06$ Pa $T := 39 + 273$ K $\mu := 19.07 \cdot 10^{-6}$ Pa-s

$Q_i := 0.025$ Pa-m^3/s ... leak rate $M := 28.97$ kg/kgmol

$C_{1upper} := 110$ lit/s $C_{2upper} := 55$ lit/s d_lower := 0.05 m $L_{lower} := 0.5$ m

$R_u := 8314.34$ J/kgmol.K

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Calculations:

Net conductance of upper part, conductances in series:

$$C\_o\_upper := \left(\frac{1}{C_{1upper}} + \frac{1}{C_{2upper}}\right)^{-1} \quad \text{lit/s}$$

i.e. C_o_upper = 36.6667 lit/s

Net conductance of lower part, C_lower:

$$p_{avg} := \frac{p_1 + p_2}{2}$$ i.e. $p_{avg} = 0.09$ Pa ... avg pressure through the tube

Mean free path, λ at 39 C, for air:

$\lambda(p_{avg}, \mu, T, M) = 0.0795$ m .... mean free path at a pressure of p = 0.09 Pa

Kn(p, μ, T, M, d_lower) = 0.5722 ...Knudsen number = λ/d_lower

i.e. Kn > 0.3

Therefore, it is Free mol. flow in the 50 mm dia tube.

Then, we use the eqn for conductance for the tube with L/d = 10:

$$C\_o\_lower := \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{\frac{1}{2}} \cdot \left(\frac{d\_lower^2}{10 + \frac{4}{3}}\right)$$ i.e. C_o_lower = 0.02758 m^3/s

i.e. C_o_lower := 27.58 lit/s

Then, net conductance of both upper and lower tubes (in parallel) is:

C_o := C_o_upper + C_o_lower lit/s

i.e. C_o = 64.2467 lit/s

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Then, throughput:

$Q := C\_o \cdot (p_1 - p_2)$ i.e. $Q = 3.8548$ **Pa-lit/s .. Ans.**

And, total throughput throuh the pump, Q_pump:

$Q_{pump} := Q + Q_i \cdot 1000$ Pa-lit/s

i.e. $Q_{pump} = 28.8548$ **Pa-lit/s .... Ans.**

And, pump speed would be:

$$S_p := \frac{Q_{pump}}{p_2} \quad \text{lit/s}$$

i.e. $S_p = 480.9133$ **lit/s .... Ans.**

Prob.7.7. A vacuum system having a volume of 3.0 m^3 and a surface area of 10 m^2 is initially pumped down to a pressure of 10 mPa and 300 K. The ultimate pressure of the system is 20 nPa. At the end of 1 hr, the specific outgassing rate is 400 nPa-m/s, and the constant in the outgassing rate curve is t. = 1 hr. It is desired to reduce the pressure to 1.0 μPa in 4 hours with an ion pump. The pump is connected to the system through a tube having a total conductance of 1.20 m3/s. Determine the required pumping speed of the ion pump. If the total length of the tube is 300 mm, determine the required tube inside diameter.[1]

Solution:

Data:

$q_1 := 400 \cdot 10^{-9}$ Pa-m/s t_prime := 3600 sec = 1 hr A := 10 m^2 V := 3.0 m^3

$p_u := 20 \cdot 10^{-9}$ Pa $t_1 := 3600$ sec..= 1 hr..outgassing const.

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$p := 1.0 \cdot 10^{-6}$ Pa .... desired pressure $t := 14400$ sec = 4 hrs

$C_o := 1.2$ m3/s ... total conductance of tube between pump and system

$L := 0.3$ m ... length of tube

$R_u := 8314.34$ kg/kgmol.K

$T := 300$ K

$M := 28.97$ kg/kmol

Recollect the Mathcad Function we wrote in Example 7.3, for pump down to high vacuum:

$$Sp\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, t) :=$$

$$\begin{bmatrix} Q_o \leftarrow q_1 \cdot A \cdot \exp\left(\frac{t\_prime}{t_1}\right) \\ S_o \leftarrow \frac{V}{t_1} + \frac{Q_o \cdot \exp\left(\frac{-t}{t_1}\right)}{p - p_u} \\ check \leftarrow \exp\left(-S_o \cdot \frac{t}{V}\right) \\ \begin{bmatrix} \text{"Const.Q\_o (Pa-m\^3/s"} & \text{"System Pumping Speed S\_o (m\^3/s)"} & \text{"check condition (almost zero)"} \\ Q_o & S_o & check \end{bmatrix} \end{bmatrix}$$

Applying this Function, we get:

$$Sp\_pumpdown\_to\_high\_vacuum(q_1, t\_prime, A, V, p_u, t_1, p, t) =$$

"Const.Q_o (Pa-m^3/s"	"System Pumping Speed S_o (m^3/s)"	"check condition (almost zero)"
$1.0873 \cdot 10^{-5}$	0.204	0

i.e. $S_o := 0.204$ **m3/s .... system pumping speed required.**

Then, pump speed is given by:

$$S_p := \left(\frac{1}{S_o} - \frac{1}{C_o}\right)^{-1}$$

i.e. $S_p = 0.2458$ **m3/s = 245.8 lit/s.... speed of pump ...Ans.**

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Dia of tube is found now:

Flow is free molecular. So, for short pipe, we have:

$$C_o = \left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{0.5} \cdot \frac{d^2}{\left(\frac{L}{d} + \frac{4}{3}\right)} \qquad \text{m3/s = 1.2 m3/s .... conductance}$$

Using the Mathcad Solve block:

Let d := 0.1 m ... guess value of tube dia

Given

$$\left(\frac{\pi \cdot R_u \cdot T}{18 \cdot M}\right)^{0.5} \cdot \frac{d^2}{\left(\frac{L}{d} + \frac{4}{3}\right)} = 1.2$$

Find(d) = 0.1732 m.... tube dia

i.e. Required tube dia, d = 0.1732 m = 173.2 mm ... Ans.

Prob.7.8. A mechanical pump is used to evacuate a space having a volume of 8.0 m3. The outgassing rate is negligible. The variation of the pump speed and the piping conductance is given in the following table. Using a numerical technique, such as the Runge-Kutta method, determine the time required to reduce the pressure of the space from an initial pressure of 100 kPa to a final pressure of 10 Pa.

Suggestion: The pump-down equation may be written as follows: dp/dt = —S_s .p/V. If we let y = ln p, then the pump-down equation becomes: dy/dt =(- S_s/V) = -(l/ V)(l/S_p + l/ C_o)$^{-1}$ This expression may then be solved numerically.[1]

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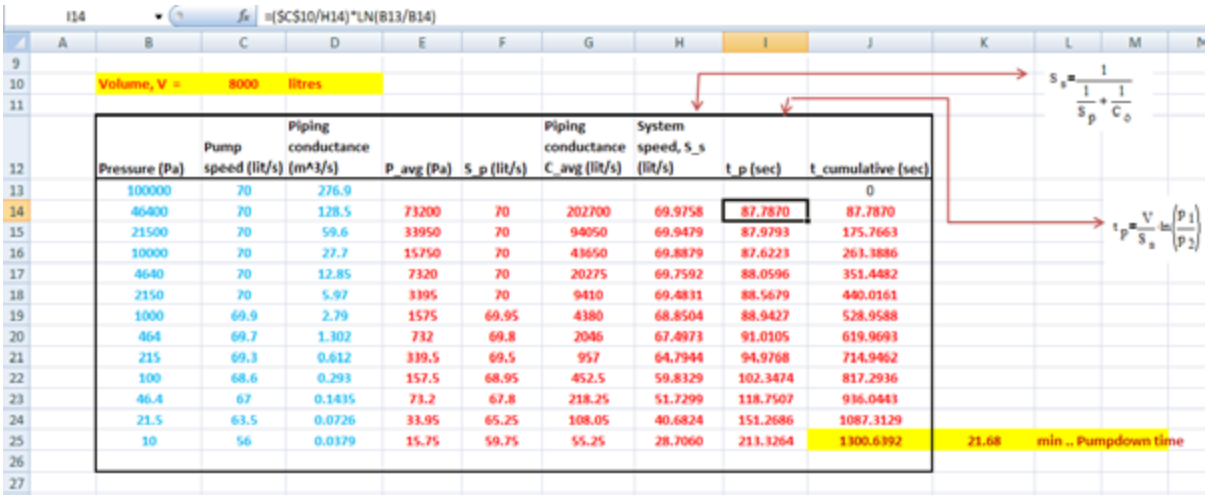
Pressure (Pa)	Pump Speed (dm^3/s)	Piping Conductance (m^3/s)
100,000	70	276.9
46,400	70	128.5
21,500	70	59.6
10,000	70	27.7
4,640	70	12.85
2,150	70	5.97
1,000	69.9	2.79
464	69.7	1.302
215	69.3	0.612
100	68.6	0.293
46.4	67.0	0.1435
21.5	63.5	0.0726
10	56.0	0.0379

Solution:

It is convenient to solve this problem in Excel:



Here, pump down time is calculated for 12 segments of pressures, and then total time for pump down is the sum of times taken for each segment.

From the given data, average pressure for the first step is = (100,000 + 46,400) / 2, Pa.

Similarly, average pumping speed and average conductances are calculated. Now, for the first segment, system pumping speed (S_s) and the pump down time t_p are calculated (see the formulas shown in the worksheet). Next, it is very easy to repeat these steps for the rest of the steps, by selecting the concerned cells and dragging the corners downwards. Last column (i.e. column J) gives the cumulative time for each step, and the last cell in that column gives the pump down time from 100,000 Pa to 10 Pa. = **1300.6392 sec = 21.68 min.**

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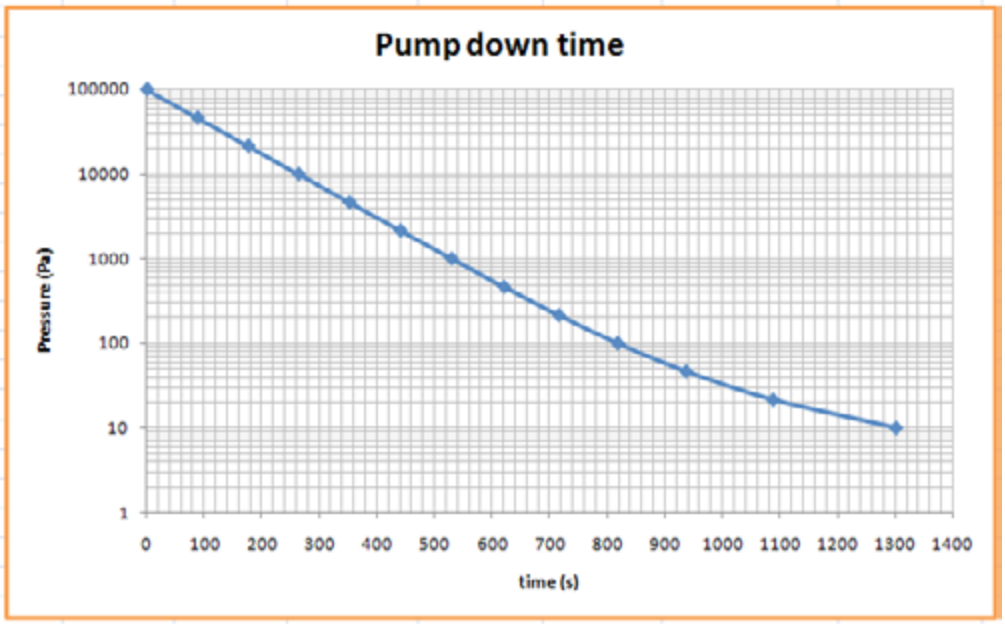
Let us draw the pump down curve:

From the above worksheet, get the following Table:

t_cum (s)	Pressure (Pa)
0.00001	100000
87.78696019	46400
175.7662816	21500
263.3886127	10000
351.4482494	4640
440.0161201	2150
528.9588058	1000
619.9693391	464
714.9461845	215
817.2935706	100
936.0442503	46.4
1087.312856	21.5
1300.639247	10

In the Table, first entry under t_cum is changed to 0.00001, since if it is zero, having a log scale for Y-axis becomes a problem; so, we put a figure nearly equal to zero. Now, draw and format the graph in Excel:



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Mathcad Solution:

Along the same lines, we write the Mathcad solution, and verify that the same results are obtained.

Here, we first write the given data as a Matrix, MM, as shown below.

	Pres. (Pa)	Sp (llit/s)	C_pipe(m3/s)
MM :=	100000	70	276.9
	46400	70	128.5
	21500	70	59.6
	10000	70	27.7
	4640	70	12.85
	2150	70	5.97
	1000	69.9	2.79
	464	69.7	1.302
	215	69.3	0.612
	100	68.6	0.293
	46.4	67	0.1435
	21.5	63.5	0.0726
	10	56	0.0379

Now, extract the Pressure (zero'th column of Matrix MM), Pump speed Sp (1st column) and Pipe conductance C_pipe (2nd column), as vectors:

$$pressure := MM^{\langle 0 \rangle} \qquad S_p := MM^{\langle 1 \rangle} \qquad C_{pipe} := MM^{\langle 2 \rangle} \cdot 1000$$

Now, we easily write the Mathcad Function to get average pressure, average pump speed and average Pipe conductance, and System pumping speed, S_s, pump down time for each step (t_p), and the cumulative time (tp_cum). We have repeat the steps for all the 12 segments with **for i = 1;12**…construct in Mathcad programming:

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$$\text{Pumpdown\_time}(V, \text{pressure}, S_p, C_{pipe}) := \left| \begin{array}{l} tp\_cum \leftarrow 0 \\ \text{for } i \in 1..12 \\ \quad p_{avg} \leftarrow \dfrac{\text{pressure}_i + \text{pressure}_{i-1}}{2} \\ \quad S_{p\_avg} \leftarrow \dfrac{S_{p_i} + S_{p_{i-1}}}{2} \\ \quad C_{pipe\_avg} \leftarrow \dfrac{C_{pipe_i} + C_{pipe_{i-1}}}{2} \\ \quad S_s \leftarrow \left(\dfrac{1}{S_{p\_avg}} + \dfrac{1}{C_{pipe\_avg}} \right)^{-1} \\ \quad t_{p_i} \leftarrow \dfrac{V}{S_s} \cdot \ln\left(\dfrac{\text{pressure}_{i-1}}{\text{pressure}_i} \right) \\ \quad tp\_cum \leftarrow tp\_cum + t_{p_i} \\ \left[\begin{array}{ll} \text{"Cumulative time (sec)"} & \text{"time for each step (sec), as a vector"} \\ tp\_cum & t_p \end{array} \right] \end{array} \right.$$

Applying this Function for this problem:

V = 8000 lit.

$$\text{pressure} := MM^{\langle 0 \rangle} \qquad S_p := MM^{\langle 1 \rangle} \qquad C_{pipe} := MM^{\langle 2 \rangle} \cdot 1000$$

We get:

$$\text{Pumpdown\_time}(V, \text{pressure}, S_p, C_{pipe}) =$$

"Cumulative time (sec)"	"time for each step (sec), as a vector"
$1.3006 \cdot 10^3$	{13,1}

We see that the pump down time (i.e. cumulative time of all steps) = 1300.6 sec, same as obtained earlier with Excel.

Next, **time for each step** is given as a vector of the output Matrix. It is in the 1st row, 1st column (Remember: default numbering for rows and columns starts from zero):

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$$\text{Pumpdown\_time}\left(V, \text{pressure}, S_p, C_{\text{pipe}}\right)_{1,1} =$$

	0
0	0
1	87.787
2	87.9793
3	87.6223
4	88.0596
5	88.5679
6	88.9427
7	91.0105
8	94.9768
9	102.3474
10	118.7507
11	151.2686
12	213.3264

Note: These values are exactly the same as obtained earlier with Excel, see column I in the Excel worksheet.

Solution in GNU Octave: (free software compatible with MATLAB):

Name of the m-file is: Prob.7.8_pumpdown_time_with_RVP.m

% Prob.7.8. A mechanical pump is used to evacuate a space having a

% volume of 8.0 m3. The outgassing rate is negligible. The variation of the pump speed and the piping conductance is given in the following table. Using a numerical technique, such as the Runge-Kutta method, determine the time required to reduce the pressure of

% the space from an initial pressure of 100 kPa to a final pressure of 10 Pa.

%

```
P = [100000  46400 21500 10000 4640   2150   1000   464    215    100    46.4 ...
       21.5   10]; %Pa

S_p = [70     70     70     70     70     70     69.9   69.7   69.3   68.6   67     63.5
       ...
       56]; % lit/s

C = [276.9   128.5  59.6   27.7   12.85  5.97   2.79   1.302  0.612 ...
```

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```
        0.293  0.14350.07260.0379]; % m^3/s

Vol = 8000; % lit
for i = 2:13
   P_avg(i-1) = (P(i) + P(i-1)) /2; %Pa
   S_p_avg(i-1) = (S_p(i) + S_p(i-1)) / 2; %lit/s
   C_avg(i-1) = (C(i)*1000 + C(i-1)*1000) / 2 ; % lit/s
   S_s(i -1) = 1 / ((1/S_p_avg(i-1)) + (1 / C_avg(i-1)));%lit/s
   time(i - 1) = (Vol / S_s(i -1)) * log(P(i-1)/P(i)); %sec
endfor

time_cum(1) = time(1);
for i = 2:12
   time_cum(i) = time_cum(i-1) + time(i);
endfor
time_tot = sum(time);

Title = [ 'P_avg (Pa) ' 'time (s) ' 'time _cum (s) ']
Results = [ P_avg' time' time_cum' ]
disp ('total pump down time (sec) is: '), time_tot
t = [0.00001 time_cum]; % Note that we have included 0.00001 to the time_cum vector,
% which is corresponding to the starting pressure of 10^5 Pa.

disp ('Pressure (Pa), and cum. time (s) are: '), [P' t']
```

% plot the pump down curve:

```
semilogy(t,P), grid, title('Pump down time')

xlabel('time (s)'), ylabel('Pressure (Pa)')
```

Now, run the above script file in command window, by typing the name of the file (without the extension 'm'), i.e. Prob7.8_pumpdown_time_with_RVP.

We get:

```
> Title = P_avg (Pa) time (s) time _cum (s)

Results =
```

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73200.00000 87.78696 87.78696

33950.00000 87.97932 175.76628

15750.00000 87.62233 263.38861

7320.00000 88.05964 351.44825

3395.00000 88.56787 440.01612

1575.00000 88.94269 528.95881

732.00000 91.01053 619.96934

339.50000 94.97685 714.94618

157.50000 102.34739 817.29357

73.20000 118.75068 936.04425

33.95000 151.26861 1087.31286

15.75000 213.32639 1300.63925

total pump down time (sec) is:

time_tot = 1300.6

Pressure (Pa), and cum. time (s) are:

ans =

100000.000000000 0.000010000

46400.000000000 87.786960188

21500.000000000 175.766281641

10000.000000000 263.388612673

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4640.000000000 351.448249444

2150.000000000 440.016120079

1000.000000000 528.958805797

464.000000000 619.969339100

215.000000000 714.946184546

100.000000000 817.293570562

46.400000000 936.044250319

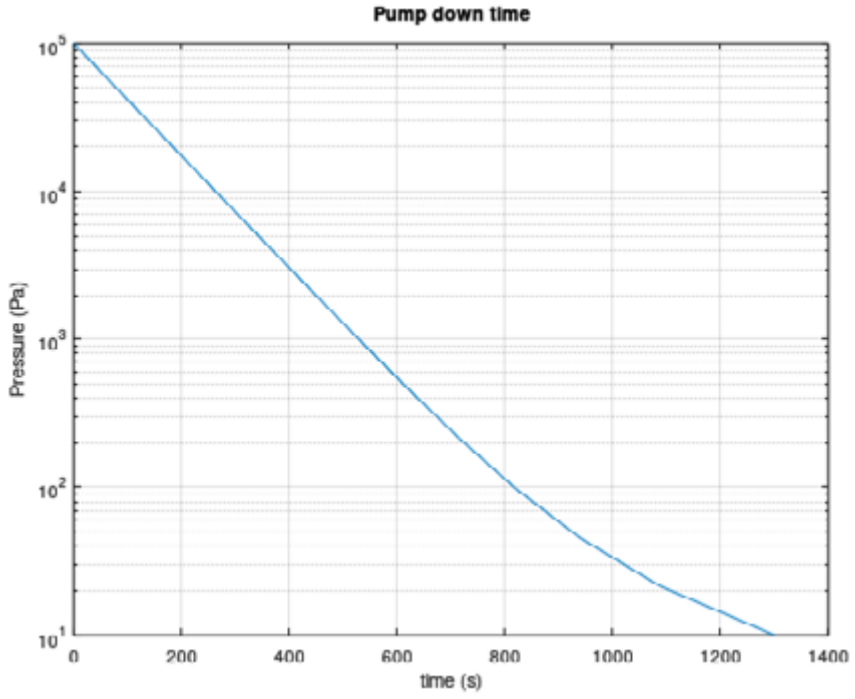
21.500000000 1087.312856419

10.000000000 1300.639247231

Note 1: In the above, time = time for each step; time_cum = cumulative time, and the last step gives the total pump down time.

Note 2: These results match with the results obtained earlier with Excel and Mathcad.

And the pump down time is plotted:



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Prob.7.9. From experimental data, the speed of a 75 mm diameter diffusion pump was found to be 160 dm3/s when pumping air at 20°C (293.2 K). Determine the Ho coefficient for the pump.[1]

Solution:

For air at 20 C, conductance of an aperture in molecular flow is (Ref: Leybold Fundamentals):

Conductance of an aperture in molecular flow is given by: [1]

$$C\_mol = \left(\frac{\pi \cdot R_u \cdot T}{32 \cdot M}\right)^{\frac{1}{2}} \cdot d\_aperture^2 \quad m^3/s$$

where

$R_u = 8314.34$ J/kgmol.K T = temp, K

$M := 28.97$ kg/kmol.... Mol. wt. of air

For air at 20 C, this becomes:

$C\_mol = 11.6 \cdot A\_aperture$ **...lit/s... where, A is in cm^2**

By data:

$d\_aperture := 7.5$ cm $Sp\_diff := 160$ lit/s

Then: $A\_aperture := \frac{\pi \cdot d\_aperture^2}{4}$ i.e. $A\_aperture = 44.1786$ cm^2

Therefore, aperture conductance in mol. flow:

$C\_mol := 11.6 \cdot A\_aperture$ lit/s

i.e. $C\_mol = 512.4723$ lit/s

But, given that pumping speed of Diffusion pump is: Sp_diff = 160 lit/s

Ho coeff is defined as the ratio of actual pump speed to theoretical pump speed:

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i.e. $Ho\_coeff := \frac{Sp\_diff}{C\_mol}$

i.e. $Ho\_coeff = 0.3122$

i.e. Ho coeff is 0.3122 .... Ans.

Prob.7.10. Determine the pumping speed for a parallel-plate cryopump that has the warm surface maintained at 300 K and the cold surface at 78 K. The gas being pumped is CO2, which has a molecular weight of 44. The area of the cryopump is 2.50 m2, and the pressure to be maintained by the pump is 25 μPa. The vapor pressure of CO2 at 78 K is 3.28 μPa.[1]

Solution:

Data:

$p_v := 3.28 \cdot 10^{-6}$ Pa ... vap pressure of CO2 at 78 K

$T_1 := 300$ K .. warm surface temp

$T_2 := 78$ K ... cryosurface temp

$M_{CO2} := 44$ g/mol... mol. wt. of CO2

$p := 25 \cdot 10^{-6}$ ...Pa ...operating pressure

$A := 2.5$ m^2 ... cryopump surface area

$R_u := 8314.34$ J/kg mol.K .... Universal gas const.

To find Sp, the required pumping speed:

Sticking coeff for a cryopanel at 77.8 K and warm surface temp of 300 K is related to Mol. wt of gas as follows [Ref. 1]:

$f = 0.453 + 0.256 \cdot \log(M)$ ..for M<= 137 g/mol

$f = 1$ ...for M > 137 g/mol

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Therefore, for CO2 (M = 44 kg/kmol), we have:

$$f := 0.453 + 0.256 \cdot \log\left(M_{CO2}\right)$$

i.e. $f = 0.8737$ **....sticking coeff for CO2**

Calculations:

Then, we have: Ultimate pressure:

$$p_u := \frac{p_v}{2} \cdot \left[1 + \left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\right]$$

i.e. $p_u = 4.8563 \cdot 10^{-6}$ ...Pa ... ultimate pressure

For a simple, parallel plate cryopump:

Factor G is given by:

$$G := (1 - f) \cdot \left(\frac{T_1}{T_2}\right)^{\frac{1}{2}} \cdot \left[1 - \frac{p_u}{p} \cdot \left[1 - \left(\frac{T_2}{T_1}\right)^{\frac{1}{2}}\right]\right]$$

i.e. $G = 0.2241$

Therefore, pumping speed per unit area is given by:

$$S_{p\_by\_A} := \frac{\left(\frac{2 \cdot R_u \cdot T_1}{\pi \cdot M_{CO2}}\right)^{\frac{1}{2}} \cdot \left(1 - \frac{p_u}{p}\right) \cdot f}{1 + \left(\frac{p_u}{p}\right) \cdot \left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}} - 1\right] + G}$$

i.e.

$S_{p\_by\_A} = 94.7988$ **m/s.. = (Sp / A)... pumping speed per unit area of cryosurface ..**

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Therefore, pumping speed is:

$S_p := S_{p\_by\_A} \cdot A$

i.e. $S_p = 236.9969$ **m^3/s .. Pumping speed .... Ans.**

Prob.7.11. In a parallel-plate cryopump, the surface area is 4.65 m2, and the warm-surface temperature is 300 K. If the gas being pumped is nitrogen and the sticking coefficient is f = 1, determine the temperature of the cold surface to maintain a pumping speed of 610 m3/s and a pressure within the system of 1.25 mPa. The vapor-pressure curve for nitrogen may be expressed as:

$\ln(p_v) = C1 - (C2/T)$

where C1 = 22.535067 and C2 = 827.23797, if p is in Pa and T is in K.[1]

Solution:

Data:

$T_1 := 300$ K .. warm surface temp

$T_2 := 30$ K ... **cryosurface temp...guess value**

$M_{N2} := 28$ g/mol... mol. wt. of N2

$p := 1.25 \cdot 10^{-3}$ ...Pa ...operating pressure

$A := 4.65$ m^2 ... cryopump surface area

$R_u := 8314.34$ J/kg mol.K .... Universal gas const.

$S_p := 610$ m^3/s

$C1 := 22.535067$ $C2 := 827.23797$

Calculations:

Use the Mathcad Solve block to solve: pv, pu and T2 simultaneously, to satisfy the given criteria:

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Given

$$\ln(p_v) = C1 - \frac{C2}{T_2}$$ ..vapor pressure for N2

$$p_u = \frac{p_v}{2}\cdot\left[1+\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\right]$$ ...ultimate pressure of cryopump

$$\frac{S_p}{A} = \left(\frac{2\cdot R_u\cdot T_1}{\pi\cdot M_{N2}}\right)^{\frac{1}{2}}\cdot\frac{\left(1-\frac{p_u}{p}\right)}{1+\left(\frac{p_u}{p}\right)\cdot\left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}-1\right]}$$

..Sp/A for parallel plate cryopump when sticking coeff. f = 1, Ref.[1]

$$\text{Find}(p_v, p_u, T_2) = \begin{bmatrix} 1.1053\cdot10^{-4} \\ 2.4249\cdot10^{-4} \\ 26.141 \end{bmatrix}$$

i.e. we get:

$T_2 = 26.141$ **K ... cryosurface temp .... Ans.**

$p_v = 1.1053\cdot10^{-4}$ **Pa .... vapor pressure of N2 at temp. T2 ... Ans.**

$p_u = 2.4249\cdot10^{-4}$ **Pa ... ultimate pressure of cryopump ... Ans.**

Excel Solution:

It is quite easy to solve the above problem in Excel, using goal seek:

First, assume a guess value for T2, say 30 K. Proceed with the calculations and find the (Sp/A), i.e. pumping speed per unit area. Both Sp and A are given in data. So find (Sp/A) as per data, and this will certainly be different from the (Sp/A) just calculated in worksheet with guess value of T2. Apply Goal Seek in Excel to make them equal by changing T2.

Worksheets before applying Goal Seek and after applying Goal Seek are shown below:

Before applying Goal seek:

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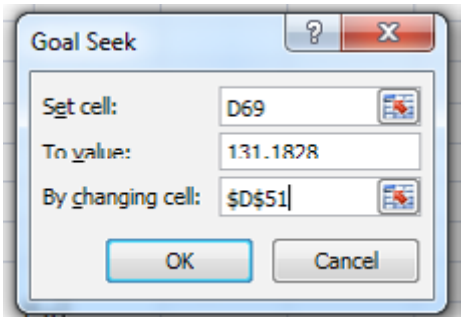
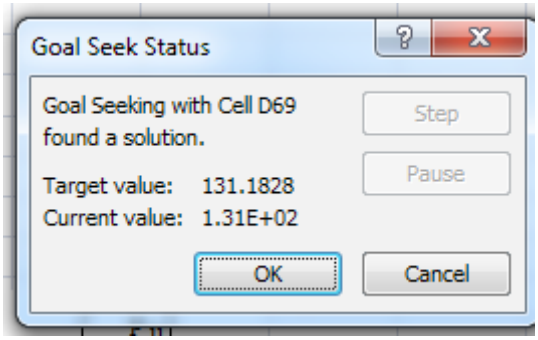
	A	B	C	D	E	F	G	H	I	J
48										
49		Data:								
50		Warm surface temp:	T_1	300	K					
51		Cryosurface temp:	T_2	30	K ....--->	30 K is guess value. Later corrected by Goal Seek.				
52		Mol wt of N2:	M_N2	28	kg/kmol					
53		Operating pressure:	p	1.25E-03	Pa					
54		Cryopump surface area:	A	4.65	m^2					
55		Universal gas const.	R_u	8314.34	J/kgmol.K					
56		Pumping speed of cryopump:	S_p	610	m^3/s					
57		Const. in vap pr. Eqn for N2:	C_1	22.53507						
58		Const. in vap pr. Eqn for N2:	C_2	827.238						
59										
60										
61		Calculations:								
62										
63		Sp_by_A	Sp_by_A	131.1828	m/s	...given (Sp/A) in data.				
64		vap. Pr of N2 at T2:	p_v	0.006477						
65		Ultimate pressure:	p_u	0.013479						
66			Num_A	238.1418						
67			Num_B	-9.78E+00						
68			Denom_A	24.3164						
69		Pumping speed per unit area:	Sp_by_A	-9.58E+01		→	$\frac{S_p}{A}=\left(\frac{2\cdot R_u\cdot T_1}{\pi\cdot M_{N2}}\right)^{\frac{1}{2}}\frac{\left(1-\frac{p_u}{p}\right)}{1+\left(\frac{p_u}{p}\right)\cdot\left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}-1\right]}$				
70										
71										
72										
73										

Apply Goal seek i.e. (Data → WhatIf analysis → Goal seek:



After applying Goal seek:



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	A	B	C	D	E	F	G	H	I	J
48										
49		Data:								
50		Warm surface temp:	T_1	300	K					
51		Cryosurface temp:	T_2	26.14096	K ....--->	30 K is guess value. Later corrected by Goal Seek.				
52		Mol wt of N2:	M_N2	28	kg/kmol					
53		Operating pressure:	p	1.25E-03	Pa					
54		Cryopump surface area:	A	4.65	m^2					
55		Universal gas const.	R_u	8314.34	J/kgmol.K					
56		Pumping speed of cryopump:	S_p	610	m^3/s					
57		Const. in vap pr. Eqn for N2:	C_1	22.53507						
58		Const. in vap pr. Eqn for N2:	C_2	827.238						
59										
60										
61		Calculations:								
62										
63		Sp_by_A	Sp_by_A	131.1828	m/s	...given (Sp/A) in data.				
64		vap. Pr of N2 at T2:	p_v	0.000111						
65		Ultimate pressure:	p_u	0.000242						
66			Num_A	238.1418						
67			Num_B	8.06E-01						
68			Denom_A	1.463184						
69		Pumping speed per unit area:	Sp_by_A	1.31E+02						
70										
71										
72										
73										

$$\frac{S_p}{A} = \left(\frac{2 \cdot R_u \cdot T_1}{\pi \cdot M_{N2}}\right)^{\frac{1}{2}} \cdot \frac{\left(1 - \frac{p_u}{p}\right)}{1 + \left(\frac{p_u}{p}\right)\left[\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}} - 1\right]}$$

Note that value of T2 obtained after Goal Seek is: T2 = 26.141 K in cell D51.

This value, and also values of p_v and p_u calculated by Goal seek agree with the corresponding values obtained by Mathcad.

Engineering Equation Solver (EES) Solution:

It is most convenient to solve this problem in EES. Equations can be written in any order, and since all the equations are solved simultaneously, the unknown temp T_2 is automatically calculated. Following is the code, and results:

$UNITS SI kg m kPa K

"Prob.7.11. In a parallel-plate cryopump, the surface area is 4.65 m2, and the warm-surface temperature is 300 K. If the gas being pumped is nitrogen and the sticking coefficient is f = 1, determine the temperature of the cold surface to maintain a pumping speed of 610 m3/s and a pressure within the system of 1.25 mPa. The vapor-pressure curve for nitrogen may be expressed as:

ln(pv) = C1 - (C2/T)

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where C1 = 22.535067 and C2 = 827.23797, if p is in Pa and T is in K.[1]"

"Solution:"

"Inputs: "

T_1 = 300 "K ... temp of warm surface"

"T_2 = temp of cold surface .... to be found out"

f = 1 "sticking coeff."

M_N2 = 28 "kg/kmol ... mol wt of N2"

S_p = 610 "m^3/s ... pumping speed of cryopump"

A = 4.65 "m^2 ... surface area of cryopump"

R_u = 8314.34 "J/kgmol.K ... Universal gas const."

p = 1.25E-03 "Pa ... pressure to be maintained"

C1 = 22.535067 "const. in vap pr curve of N2"

C2 = 827.23797 "const. in vap pr curve of N2"

"Calculations:"

ln(p_v) = C1 - C2 /T_2 " Pa ...vap pr of N2 when T_2 is in K"

p_u = (p_v/ 2) * (1 + (T_1 / T_2)^(1/2))

AA = (2 * R_u * T_1 / (pi * M_N2))^(1/2)

BB = 1 - p_u / p

CC = 1 + (p_u / p) * ((T_1 / T_2)^(1/2) - 1)

S_p/ A = AA * BB / CC

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"Running the program, we get: T_2 = 26.14 K .... Ans."

Results:

Unit Settings: SI K kPa kJ mass deg

$A = 4.65$ [m^2]	$AA = 230.1$ [-]	$DD = 0.006$	$C1 = 22.54$
$C2 = 827.2$	$CC = 1.463$	$f = 1$	$M_{N2} = 28$ [kg/kmol]
$p = 0.00125$	$p_u = 0.0002425$ [Pa]	$p_v = 0.0001105$ [Pa]	$R_u = 8314$ [J/kgmol.K]
$S_p = 610$ [m^3/s]	$T_1 = 300$ [K]	$T_2 = 26.14$ [K]	

"----------"

Prob.7.12. A Santler cryopumping array is used to maintain a pressure of 85 nPa in a space environmental chamber. The warm surface is at a temperature of 20°C (293.2 K) and the cryopump temperature is 20 K. The gas being pumped is nitrogen, which has a vapor pressure of 6.0 nPa at 20 K. The capture coefficient for the array is C_c = 0.45. For an outgassing load of 35 μPa-m3/s, determine the required frontal area of the array. [1]

Solution:

Data:

$T_1 := 293.2$ K .. warm surface temp

$T_2 := 20$ K ... **cryosurface temp.**

$M_{N2} := 28$ g/mol... mol. wt. of N2

$p_v := 6.0 \cdot 10^{-9}$ Pa ... vap pressure of N2 at 20 K

$p := 85 \cdot 10^{-9}$ ...Pa ...operating pressure

$C_c := 0.45$ ... Capture coeff of cryopump array

$R_u := 8314.34$ J/kg mol.K .... Universal gas const.

$Qi := 35 \cdot 10^{-6}$ Pa-m^3/s ... outgassing load

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Calculations:

$$p_u := \frac{p_v}{2}\cdot\left[1+\left(\frac{T_1}{T_2}\right)^{\frac{1}{2}}\right] \qquad \text{Pa ... ultimate pressure}$$

i.e. $p_u = 1.4487\cdot 10^{-8}$ Pa

Pumping speed per unit frontal area of array is given by: (Ref. [1]:

$$\frac{S_p}{A} = \frac{C_c}{2-C_c}\cdot\left(\frac{2\cdot R_u\cdot T_1}{\pi\cdot M}\right)^{\frac{1}{2}}\cdot\left(1-\frac{p_u}{p}\right) \quad \text{...m/s, where T1 = warm surface temp (K)}$$

i.e. $Sp\_by\_A := \frac{C_c}{2-C_c}\cdot\left(\frac{2\cdot R_u\cdot T_1}{\pi\cdot M}\right)^{\frac{1}{2}}\cdot\left(1-\frac{p_u}{p}\right)$ m/s

i.e. $Sp\_by\_A = 56.701$ m/s

Now, by definition of throughput, we have:

$Qi = Sp\_by\_A\cdot A\cdot(p-p_v)$ .. Outgassing rate

i.e. $A := \frac{Qi}{Sp\_by\_A\cdot(p-p_v)}$

i.e. $A = 7.814$ **m^2 .... frontal area required for array .... Ans.**

7.9 COMMERCIAL SOFTWARE FOR VACUUM CALCULATIONS

Vacuum simulation is done in design stage to know how the components/systems would behave in real life. It helps in identifying the problems and solving them in the design stage itself without actually investing in buying and installing costly components.

There are many specialized software available for this purpose:

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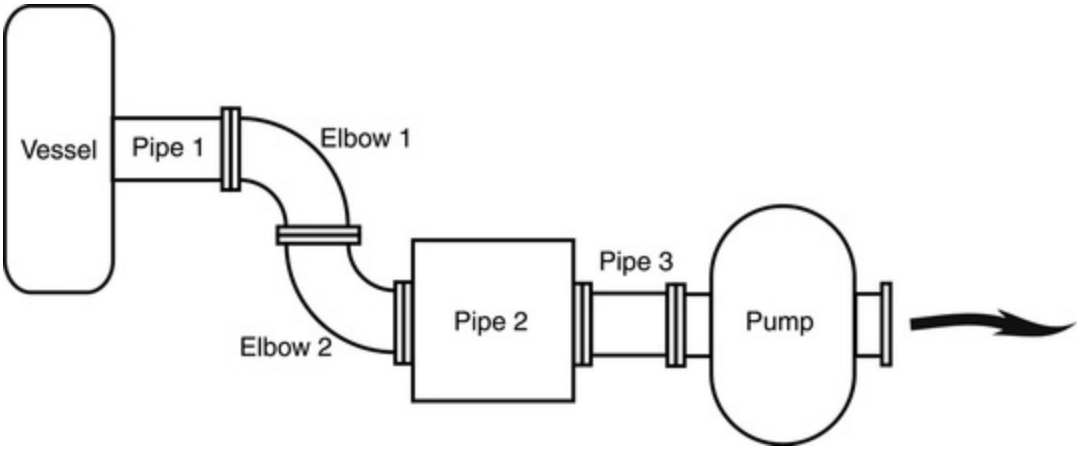
1. **VacTran:** Software from Professional Engineering Computations (PEC), California, USA. See www.vactran.com. Software developed since 1987. Extract from their website:
   What does VacTran do?



- Calculates the pump down time of a vacuum system, with and without gas loads
- Models conductance elements such as pipes and elbows, and determine their effect on the delivered speed of the system
- Models raw data conductance elements representing conductance vs. pressure
- Calculates the rate of pressure rise for a vacuum vessel based on its gas load
- Models vacuum pumps and raw data gas loads with full editing features, including a pump curve digitizer utility
- Models surface outgassing, permeations, and leaks, and calculate the rate of rise for a vacuum vessel
- Graphs a multitude of vacuum system calculations with flexible plotting parameters that are easily changed
- Creates professional-looking graphs that can be used in publications or presentations or saved in standard graphics formats

Ref: Vacuum Science World-An Introduction to Vacuum Simulation:

2. **PumpCalc:** This is for simulating simple systems. Proprietary software of Edwards Vacuum, U.K.
3. **TransCalc:** This is based on duct flow prediction techniques, and gives solutions over all pressure ranges.
4. **Pascal:** It is a flow optimization tool based on empirical data gained from existing pumps.
   (**Ref. for Pascal**: https://www.aimcal.org/uploads/4/6/6/9/46695933/corcoran_presentation.pdf)

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Model capabilities

- Each pump/component is modeled as an **individual** vacuum element
- Vacuum system layout can be fully 2-dimensional
- It is possible to use **multiple chambers** within a single system
- It is possible to calculate two or more independent vacuum systems at once
- Pumps/valves are **switchable**; switching is controlled either by pressure, time or by another vacuum element
- Certain **boundary conditions** (pressure or flow b.c.) can be applied at any place of the vacuum system

Physical effects taken into account

- Desorption (at this time within chambers only)
- Internal volume of each vacuum element
- Pressure- and time dependent change in gas temperature within the chamber/s (during pump down), due to thermodynamic effects
- Transient operation of mechanical boosters using FCs

On line vacuum calculations:

2020/01/27

Leybold Launches Two Vacuum Calculation and Simulation Tools

Vacuum technology specialist, Leybold, has developed two new online tools to assist customer's pump choice and layout of complete vacuum systems: The Pump Finder and the calculation tool LEYCALC. With these new web-based tools, users can select and build their vacuum solutions online. They are designed to be used for two different use cases: The homepage https://calc.leybold.com/en/lp leads to both the Pump Finder and LEYCALC, the vacuum system calculation tool. Users with vacuum know-how can use LEYCALC to calculate the behavior and performance of vacuum systems in detail. The Pump Finder guides even beginners to suitable products by a questionnaire.

Also, for on-line calculation of evacuation time, see:
https://www.engineeringtoolbox.com/vacuum-evacuation-time-d_844.html
On-line flow and pressure (vacuum) converters:
https://www.vacuubrand.com/us/page1228.html

5. **MolFlow:** is a Monte Carlo simulation package developed at CERN.
6. **VacSim:** is a PC based simulation package which can predict how the pressure varies with time, throughput, pump speed and back-streaming. Inherently, simple to use.

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7. **COMSOL:** Developed since 1986 in Royal Institute of Technology, Stockholm, Sweden. Used in vacuum system simulation in semiconductor processing, particle accelerators, mass spectrometers etc.
8. **ANSYS:** Well known stress analysis software based on Finite element analysis. In addition to stress analysis, it has thermal capabilities too. It can anlyse the stress and thermal distortion in pump components, evaluate cooling of components and systems etc.

7.10 REFERENCES

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7. Air products data on gases: http://www.airproducts.com/Products/Gases.aspx
8. *J.M. Pfotenhauer,* University of Wisconsin, Madison, USPAS Cryogenics Short Course, Boston, 2010
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APPENDIX – I

Matlab compatible m-files, written in free, GNU Octave software

GNU Octave programs:

GNU Octave is 'compatible' with Matlab, and is *available for free* from:

https:// www.octave.org

These programs should be able to run in Matlab.

% Interactive program to find the conductance of an orifice

% in molecular flow in lit/s, for air at 25 deg.C

% Input: radius of orifice, cm

% Output: Conductance of orifice, lit/s

% From Dushman's Table

% Author: M. Thirumaleshwar; Date: 23-11-2019

```
rad_cm = [0.1   0.2   0.3   0.4   0.5   0.6   0.7   0.8   0.9   1   2   3
    4          5     6     7     8     9     10];

C_orifice = [0.367   1.466   3.3   5.866   9.166   13.2   17.97   23.47   29.7   36.66
    146.6 330   586.6   916.6   1320   1797   2347   2970   3666];
```

% Table = [rad_cm' C_orifice'];

rad = input("enter value of radius of orifice, cm: ")

disp('orifice conductance in lit/s is:')

c_orif = interp1(rad_cm, C_orifice, rad)

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Example 1:

```
>> C_orifice_air25C_molecularflow

enter value of radius of orifice, cm: 2

rad = 2

orifice conductance in lit/s is:

c_orif = 146.60
```

Example 2:

```
>> C_orifice_air25C_molecularflow

enter value of radius of orifice, cm: 9.5

rad = 9.5000

orifice conductance in lit/s is:

c_orif = 3318
```

% Octave Function to find the mol. Flow conductance of an orifice

```
function C_orif = C_orif_air25C_molecular(rad)

% for air at 25 C:

% From Dushman's Table

% Input: radius of orifice, cm

% Output: Conductance of orifice, lit/s

% Author: M. Thirumaleshwar; Date: 23-11-2019
```

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```
rad_cm = [0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1  2  3
4  5  6  7  8  9  10];

C_orifice = [0.367  1.466  3.3  5.866  9.166  13.2  17.97  23.47  29.7 ...
36.66 146.6  330  586.6  916.6  1320  1797  2347  2970  3666]
```

% Table = [rad_cm' C_orifice'];

C_orif = interp1(rad_cm, C_orifice, rad);

Endfunction

Example 1:

>> CC=C_orif_air25C_molecular(7.5), disp ('lit/s')

CC = 2072

lit/s

Example 2:

>> CC=C_orif_air25C_molecular(8.5), disp ('lit/s')

CC = 2658.5

lit/s

%Interactive program for conductance of a tube from Dushman's Table:

% Finds molecular flow conductance of a tube for air at 25 C

% Author: M. Thirumaleshwar Date: March 2020

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```
% Ref: Dushman's Table

AA = [0.246  0.188  0.132  0.085  0.063  0.05   0.029

0.986  0.753  0.527  0.34   0.252  0.2    0.117

2.217  1.664  1.184  0.764  0.567  0.451  0.263

3.943  3.013  2.106  1.358  1.008  0.802  0.468

6.16   4.708  3.291  2.122  1.575  1.253  0.731

8.872  6.779  4.739  3.057  2.269  1.805  1.052

12.08  9.228  6.449  4.161  3.088  2.457  1.432

15.77  12.05  8.424  5.436  4.033  3.208  1.871

19.96  15.25  10.66  6.879  5.105  4.061  2.368

24.64  18.83  13.16  8.492  6.302  5.013  2.922

98.56  75.34  52.65  33.97  25.21  20.05  11.69

221.7  166.4  118.4  76.42  56.71  45.11  26.3

394.3  301.3  210.6  135.8  100.8  80.21  46.77

616    470.8  329.1  212.2  157.5  125.3  73.1

887.2  677.9  473.9  305.7  226.9  180.5  105.2

1208   922.8  644.9  416.1  308.8  245.7  143.2

1577   1205   842.4  543.6  403.3  320.8  187.1

1996   1525   1066   687.9  510.5  406.1  236.8

2464   1883   1316   849.2  630.2  501.3  292.2];
```

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```
Lbya = [1 2 4 8 12 16 30];

radius = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, ...

2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, 10.0];

x_Lbya = input("enter desired Lbya value: ")

y_radius= input("enter desired radius value, cm: ")

C_tube_xiyi = interp2(Lbya,radius,AA,x_Lbya,y_radius), disp ('lit/s')
```

Example 1:

```
>> Tube_conduct_air25C_molflow

enter desired Lbya value: 4

x_Lbya = 4

enter desired radius value, cm: 7

y_radius = 7

C_tube_xiyi = 644.90

lit/s
```

Example 2:

```
>> Tube_conduct_air25C_molflow

enter desired Lbya value: 12

x_Lbya = 12
```

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enter desired radius value, cm: 4.5

y_radius = 4.5000

C_tube_xiyi = 129.15

lit/s

Example 3:

>> Tube_conduct_air25C_molflow

enter desired Lbya value: 14

x_Lbya = 14

enter desired radius value, cm: 4.5

y_radius = 4.5000

C_tube_xiyi = 115.95

lit/s

Function to find tube conductance:

```
function tubeconduct = tube_conductance(xLbya,yradius)
% CONDUCTANCE_TUBE : function to find conductance of a tube.
% call syntax:
%       tubeconduct = conductance_tube(xLbya,yradius)
% Author: M. Thirumaleshwar. Date: 24-11-2019
```

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```
AA = [

0.246  0.188  0.132  0.085  0.063  0.05   0.029

0.986  0.753  0.527  0.34   0.252  0.2    0.117

2.217  1.664  1.184  0.764  0.567  0.451  0.263

3.943  3.013  2.106  1.358  1.008  0.802  0.468

6.16   4.708  3.291  2.122  1.575  1.253  0.731

8.872  6.779  4.739  3.057  2.269  1.805  1.052

12.08  9.228  6.449  4.161  3.088  2.457  1.432

15.77  12.05  8.424  5.436  4.033  3.208  1.871

19.96  15.25  10.66  6.879  5.105  4.061  2.368

24.64  18.83  13.16  8.492  6.302  5.013  2.922

98.56  75.34  52.65  33.97  25.21  20.05  11.69

221.7  166.4  118.4  76.42  56.71  45.11  26.3

394.3  301.3  210.6  135.8  100.8  80.21  46.77

616    470.8  329.1  212.2  157.5  125.3  73.1

887.2  677.9  473.9  305.7  226.9  180.5  105.2

1208   922.8  644.9  416.1  308.8  245.7  143.2

1577   1205   842.4  543.6  403.3  320.8  187.1

1996   1525   1066   687.9  510.5  406.1  236.8

2464   1883   1316   849.2  630.2  501.3  292.2];
```

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```
Lbya = [1     2     4     8     12     16     30];

rad_cm = [0.1    0.2    0.3    0.4    0.5    0.6    0.7    0.8    0.9    1    2    3
      4          5      6      7      8      9      10];

tubeconduct=interp2(Lbya,radius,AA,xLbya,yradius);
```

Example 1:

```
>> ZZZ=tube_conductance_air25C_dushman(4,8), disp('lit/s')

ZZZ = 842.40

lit/s
```

Example 2:

```
>> ZZZ=tube_conductance_air25C_dushman(4.5,9.5), disp('lit/s')

ZZZ = 1138.2

lit/s
```

Interactive script for conductance for air at 20C:

File Name: conductance_air20C.m

```
% Interactive program for conductance of a tube in laminar, molecular

% and transition flow, (lit/s) for air at 20 C flowing in a pipe

% of length L (cm) and diam, d(cm), at an avg. pressure, p_bar (mbar)
```

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```
% Ref: Leybolds Fundamentals

% Author: M. Thirumaleshwar. Date: February 23, 2020

disp('Finds conductance (lit/s) for air at 20 C')

disp(' ========================================')

disp('')

d = input('enter value of dia, d (cm) of pipe :')

L = input ('enter value od Length L (cm) of pipe :')

p_bar = input('enter avg pressure, p_avg (mbar):')

dp_bar = d * p_bar ; %mbar.cm

if (dp_bar >= 0.6)

   conductance = 135 * (d^3 /L) * p_bar; %lit/s

   Flow = 'laminar flow'

   disp ('dp_bar in (mbar-cm) is:')

   disp(dp_bar)

   disp('Conductance (lit/s)is:')

   disp(conductance)

endif

if (dp_bar <= 0.01)

   conductance = 12.1 * d^3 /L ;%lit/s

   Flow = 'molecular flow'
```

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```
   disp ('dp_bar in (mbar-cm) is:')
   disp(dp_bar)
   disp('Conductance (lit/s)is:')
   disp(conductance)
endif
if ((0.01 < dp_bar) && (dp_bar < 0.6))
   conductance = 135 * (d^4 / L) * p_bar ...
   + 12.1 * (d^3 /L) * (1 + 192 * d * p_bar) / (1 + 237 * d * p_bar); %lit/s
  Flow = 'transition flow'
   disp ('dp_bar in (mbar-cm) is:')
   disp(dp_bar)
   disp('Conductance (lit/s)is:')
   disp(conductance)
endif
```

Example 1:

```
>> conductance_air20C
Finds conductance (lit/s) for air at 20 C
=========================================================
enter value of dia, d (cm) of pipe :1
d = 1
```

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enter value of Length L (cm) of pipe :10

L = 10

enter avg pressure, p_avg (mbar):1

p_bar = 1

Flow = laminar flow

dp_bar in (mbar-cm) is:

1

Conductance (lit/s)is:

13.500

Example 2:

>> conductance_air20C

Finds conductance (lit/s) for air at 20 C

==========

enter value of dia, d (cm) of pipe :1

d = 1

enter value of Length L (cm) of pipe :10

L = 10

enter avg pressure, p_avg (mbar):0.02

p_bar = 0.020000

Flow = transition flow

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dp_bar in (mbar-cm) is:

0.020000

Conductance (lit/s) is:

1.2903

Example 3:

>> conductance_air20C

Finds conductance (lit/s) for air at 20 C

==========

enter value of dia, d (cm) of pipe :1

d = 1

enter value of Length L (cm) of pipe :10

L = 10

enter avg pressure, p_avg (mbar):0.001

p_bar = 0.0010000

Flow = molecular flow

dp_bar in (mbar-cm) is:

0.0010000

Conductance (lit/s)is:

1.2100

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Function to find the conductance of air at 20 C flowing through a pipe

```
function[dp_bar,conductance,Flow] = Pipe_conductance_air20C(d, L, p_bar)
   % Finds conductance (lit/s) for air at 20 C flowing in a pipe
   % of length L (cm) and diam, d(cm), at an avg. pressure, p_bar (mbar)
% Author: M. Thirumaleshwar. Date: February 23, 2020
   dp_bar = d * p_bar;
   if(dp_bar >= 0.6)
      conductance = 135 * (d^4 /L) * p_bar; % lit/s
      Flow = 'laminar flow';
   endif
   if(dp_bar <= 0.01)
      conductance = 12.1 * (d^3 / L);
      Flow = 'molecular flow' ;
   endif
   if((0.01 <dp_bar)&&(dp_bar <0.6))
      conductance = 135 * (d^4 / L) * p_bar ...
      + 12.1 * (d^3 /L) * (1 + 192 * dp_bar)/(1 + 237 * dp_bar);
      Flow = 'transition flow';
   endif
endfunction
```

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Example 1:

>> [dp_bar,conductance,Flow] = Pipe_conductance_air20C(1, 10, 0.01)

dp_bar = 0.010000

conductance = 1.2100

Flow = molecular flow

Example 2:

>> [dp_bar,conductance,Flow] = Pipe_conductance_air20C(1, 10, 0.06)

dp_bar = 0.060000

conductance = 1.8053

Flow = transition flow

Example 3:

>> [dp_bar,conductance,Flow] = Pipe_conductance_air20C(1, 10, 1)

dp_bar = 1

conductance = 13.500

Flow = laminar flow

Interactive script for Pump down time from 1 bar to 1 Pa:

File Name: Pumpdown_time_to_P_f.m

% Finds pump down time(min) for a Volume, V (lit)

% System Pumping speed, S (lit/min) to a final

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```
% pressure, P_f ( >=1 Pa)
% Author: M. Thirumaleshwar. Date: February 23, 2020
disp('Finds Pump down time from 1 bar to P_f (>= 1 Pa)')
disp('==========================================')
V = input ('enter value of Volume, V (lit) :')
P_f = input('enter value of final pressure, P_f (Pa) :')
if ( P_f < 1)
   error('P_f must be >= 1 Pa !!')
   endif
S = input('enter value of System pumping speed (lit/min) :')
if (P_f >= 10^4)
   F_s = 1;
   t = log(10^5 / P_f) * F_s * V / S;
   disp('pump down time (min) to P_f is : ')
   disp(t)
endif
if ((P_f < 10^4) && (P_f >= 10^3))
   F_s = 1.25;
   t = log (10 ) * (V / S) +log(10^4 / P_f) * (F_s * V / S);
   disp('pump down time (min) to P_f is : ')
```

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```
   disp(t)

endif

if((P_f < 10^3) && (P_f >= 10^2))

   F_s = 1.5;

   t = log (10 ) * (V / S) + log (10 ) * (1.25 *V / S) ...

   + log(10^3 / P_f) * (F_s * V / S);

   disp('pump down time (min) to P_f is : ')

   disp(t)

endif

if((P_f < 10^2) && (P_f >= 10))

   F_s = 2;

   t = log (10 ) * (V / S) + log (10 ) * (1.25 *V / S) ...

      + log (10 ) * (1.5 *V / S) ...

      + log(10^2 / P_f) * (F_s * V / S);

   disp('pump down time (min)to P_f is : ')

   disp(t)

endif

if ((P_f < 10) && (P_f >= 1))

   F_s = 4;

   t = log (10 ) * (V / S) + log (10 ) * (1.25 *V / S) ...
```

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```
    + log (10 ) * (1.5 *V / S) ...
    + log (10 ) * (2 *V / S) + log(10 / P_f) * (F_s * V / S);
  disp('pump down time (min) to P_f is : ')
  disp(t)
endif
```

Example 1:

```
>> Pumpdown_time_to_P_f
Finds Pump down time from 1 bar to P_f (>= 1 Pa)
 ========================================
enter value of Volume, V (lit) :1000
V = 1000
enter value of final pressure, P_f (Pa) :0.5
P_f = 0.50000
error: P_f must be >= 1 Pa !!
error: called from
  Pumpdown_time_to_P_f at line 11 column 3
```

Example 2:

```
>> Pumpdown_time_to_P_f
Finds Pump down time from 1 bar to P_f (>= 1 Pa)
==========================================
```

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enter value of Volume, V (lit) :1000

V = 1000

enter value of final pressure, P_f (Pa) :10

P_f = 10

enter value of System pumping speed (lit/min) :900

S = 900

pump down time (min)to P_f is :

14.711

Here is another script file to calculate the pumping speed of a cryopump:

Name of file: Prob7.10_parallel_plate_cryopump.m

%Prob.7.10. Determine the pumping speed for a parallel-plate cryopump

% that has the warm surface maintained at 300 K and the cold surface

% at 78 K. The gas being pumped is CO2, which has a molecular weight

% of 44. The area of the cryopump is 2.50 m2, and the pressure to be

% maintained by the pump is 25 mPa. The vapor pressure of CO2 at 78 K

% is 3.28 mPa.[1]

% Data:

p_v = 3.28e-06; %Pa ... vap pr of CO2 at 78 K

T_1 = 300; %K ... warm surface temp

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```
T_2 = 78; %K .... cold surface temp

M_CO2 = 44; % g/mol ... mol. wt of CO2

p = 25e-06; %Pa ... operating pressure

A = 2.5; %m^2 .... cryopump surface area

R_u = 8314.34; %kg/kmolK ... universal gas const.

% Find S_p, the required pumping speed

%
```

%Calculations:

```
f = 0.453 + 0.256 * log10(M_CO2);% sticking coeff.

disp('Value of sticking coeff is: '),f

p_u = (p_v/2) * (1 + (T_1/T_2)^(1/2));

disp('ultimate pressure in Pa is: '), p_u %ultimate pressure

%Factor G is given by:

G = (1 - f) * (T_1 / T_2 )^(1/2) * ...

(1 - (p_u/p)* (1 - (T_2 / T_1)^(1/2)));

disp('Value of const. G is: '), G

%Now, find (S_p / A):

Num_A = ((2 * R_u * T_1) / (pi * M_CO2))^(1/2);

Num_B = (1 - p_u/p)*f;

Denom_A = 1 + (p_u/p)*((T_1/T_2)^(1/2) - 1);
```

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```
S_p_by_A = (Num_A * Num_B)/ (Denom_A + G);

disp('Value of S_p/A, in m/s is: '),S_p_by_A

% Therefore, S_p is:

S_p = S_p_by_A* A; %m^3/s

disp('And, the pumping speed of cryopump in m^3/s, is: '), S_p
```

Now, run the above script file in command window, by typing the name of the file (without the extension 'm'), i.e. Prob7.10_parallel_plate_cryopump.

We get the results:

```
>> Value of sticking coeff is:

f = 0.87372

ultimate pressure in Pa is:

p_u = 0.0000048563

Value of const. G is:

G = 0.22407

Value of S_p/A, in m/s is:

S_p_by_A = 94.799

And, the pumping speed of cryopump in m^3/s, is:

S_p = 237.00
```

Note: If desired, you can change any Input parameter in the Edit window, and run the file again to get corresponding results.

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Here is one more script file to calculate the cryosurface temp of a cryopump:

Name of file: Prob7.11_parallel_plate_cryopump.m

%**Prob.7.11. In a parallel-plate cryopump**, the surface area is 4.65 m2, %and the warm-surface temperature is 300 K. If the gas being pumped is nitrogen and the sticking coefficient is f = 1, determine the %temperature of the cold surface to maintain a pumping speed of 610 m3/s and a pressure within the system of 1.25 mPa. The vapor-%pressure curve for nitrogen may be expressed as:

% ln(pv) = C1 - (C2/T)

% where C1 = 22.535067 and C2 = 827.23797, if p is in Pa and T is in K.[1]

% Data:

```
disp('Data:')

disp('Note: T in K, P in Pa,Sp in m^3/s, A in m^2,C1,C2 = constants')

disp('')

T_1 = 300            % K... warm surface temperature

T_2_guess = 40       % K ... cold surface temp ... guess value

M_N2 = 28            % kg/kmol .. mol wt of N2

p = 0.001250         % Pa .. operating pressure

A = 4.65             % m^2 ... cryopump surace area

R_u = 8314.34        % kg/kmol.K Universal gas const.

S_p = 610            % m^3/s ...pumping speed

C_1 = 22.535067      % ... const in vap pressure eqn.

C_2 = 827.23797      % .... const in vap pressure eqn.
```

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% Calculations:

```
p_v = exp(C_1 - C_2/T_2_guess); % Pa ...vap pr of N2 at T_2

p_u = (p_v/2) * (1 + (T_1/T_2_guess)^(1/2)); % Pa .. ultimate pr.

Sp_by_A = ((2 * R_u * T_1)/ (pi * M_N2))^(1/2) * (1 - p_u/p)/ ...

      (1 + (p_u/p)* ((T_1 / T_2_guess)^(1/2) - 1));

epsilon = ((S_p/A) -Sp_by_A);

while (epsilon >= 0.001)

   T_2_guess = T_2_guess -0.001;

   p_v = exp(C_1 - C_2/T_2_guess);

   p_u = (p_v/2) * (1 + (T_1/T_2)^(1/2));

   Sp_by_A = ((2 * R_u * T_1)/ (pi * M_N2))^(1/2) * (1 - p_u/p)/ ...

   (1 + (p_u/p)* ((T_1 / T_2_guess)^(1/2) - 1));

   epsilon = ((S_p/A) -Sp_by_A);

endwhile

T_2 = T_2_guess;

disp('')

disp('Results:')

disp('')

disp('Temp of cryosuface (K) is: '), T_2

disp('')
```

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disp('Vapor pressure (Pa) of N2 at T_2 is: '), p_v

disp('')

disp('Ultimate pressure (Pa) of cryopump is: '), p_u

Now, run the above script file in command window, by typing the name of the file (without the extension 'm'), i.e. Prob7.11_parallel_plate_cryopump.

We get the results:

>> Data:

Note: T in K, P in Pa, Sp in m^3/s, A in m^2, C1, C2 = constants

T_1 = 300

T_2_guess = 40

M_N2 = 28

p = 0.0012500

A = 4.6500

R_u = 8314.3

S_p = 610

C_1 = 22.535

C_2 = 827.24

Results:

Temp of cryosuface (K) is:

T_2 = 26.140

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Vapor pressure (Pa) of N2 at T_2 is:

p_v = 0.00011040

Ultimate pressure (Pa) of cryopump is:

p_u = 0.00024221

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APPENDIX – II

Design of a Thermal system for thermo-vacuum chambers

By

M. Thirumaleshwar

CRYOGENICS, Nov. 1978

Design of the thermal system of two thermovacuum chambers, recently installed for the Indian Space Research Organisation, is considered in detail. These Chambers operate in the temperature range 173 K–373 K. Two alternative systems, the gas-bypass flow system and the LN_2 injection system are analysed. Results are plotted in the form of generalized graphs. Specific results for the 2.0 m diameter thermovacuum chamber are also presented.

Design of a thermal system for thermovacuum chambers

M. Thirumaleshwar

Nomenclature

C_p	Specific heat at constant pressure, J g^{-1} K^{-1}
$\bar{c}_p$	Mean value of C_p, J g^{-1} K^{-1}
h	Enthalpy, J g^{-1}
h_{fg}	Latent heat of LN_2, J g^{-1}
$\dot{m}$	Mass flow rate, g s^{-1}
$\dot{Q}_{cond}$	Heat loss due to conduction, W
$\dot{Q}_{dissip}$	Dissipation heat load from specimen, W
$\dot{Q}_{ht}$	Heater power required, W
$\dot{Q}_L$	Heat loss to/from surroundings, W
$\dot{Q}_{Rad}$	Radiant heat load on the shroud, W
$\dot{Q}_s$	Total heat load on the shroud
T	Temperature, K
ΔT	Temperature difference, K
$\dot{W}$	Rate of work done on/by the system, W
x, y, z	Fractions as defined in the text
ϵ	Heat exchanger effectiveness

Subscripts

1–6	Refer to corresponding points in the two systems as shown in Fig. 1 and Fig. 6

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Two thermovacuum chambers (tvc's) have just been installed for the Indian Space Research Organisation (isro). One of them, installed at The Space Applications Centre, Ahmedabad is 1.2 m in diameter and 1.2 m long; and the other one, installed at isro Satellite Centre, Bangalore is 2.0 m in diameter and 2.5 m long. These Chambers would be used to test the satellite components and subsystems under the simulated conditions of Space. The operating requirements of isro for these chambers were: pressure of the order of 10^{-6} Torr and temperatures in the range 173 K to 373 K, to be varied continuously. For the larger chamber, provision had to be incorporated to provide solar simulation (beam diameter 0.6 m) in the future.

The desired pressure was obtained by a conventional vacuum system consisting of oil diffusion pumps, root pumps and mechanical pumps.

The purpose of this paper is to describe in detail the design approach to the thermal system of these chambers to meet the specifications.

Design of the thermal system

Basically, temperatures in the range 173 K to 373 K are obtained inside the chamber by passing cold/hot gaseous nitrogen (GN_2) through a thermal shroud placed inside the chamber. Two alternative thermal systems were considered: gas-bypass flow system; and a liquid nitrogen (LN_2) injection system.

Finally, the LN_2 injection system was adopted for the tvc's for reasons that will be clear later. The design approach for both these systems will be discussed in detail.

Gas-bypass flow system. This system is shown schematically in Fig. 1, (inset). The system consists of a GN_2 blower, heat exchanger, liquid nitrogen bath, heater chamber, the shroud and of course, the necessary control valves and piping. This is the type of system used by M/s. Cryo Systems in a thermovacuum chamber facility supplied to European Space Technology Centre, Noordwijk, Holland.[1]

The GN_2 blower circulates GN_2 through the system at a pressure of about 3.04×10^2 kN m^{-2}. During the cold cycle (173 K–300 K), the GN_2 from the blower, after being cooled in a cooler, passes through a heat exchanger. Then it is bifurcated into two streams. One of the streams is passed through a LN_2 bath where it is cooled to a low temperature. This stream is then mixed with the other warm stream and the resultant gas stream enters the shroud. By suitably controlling the flow rates of the two streams it is possible to attain the desired temperature at the inlet to the shroud. The return stream from the shroud passes through the heat exchanger, thus pre-cooling the incoming stream, and then proceeds to the suction of the blower.

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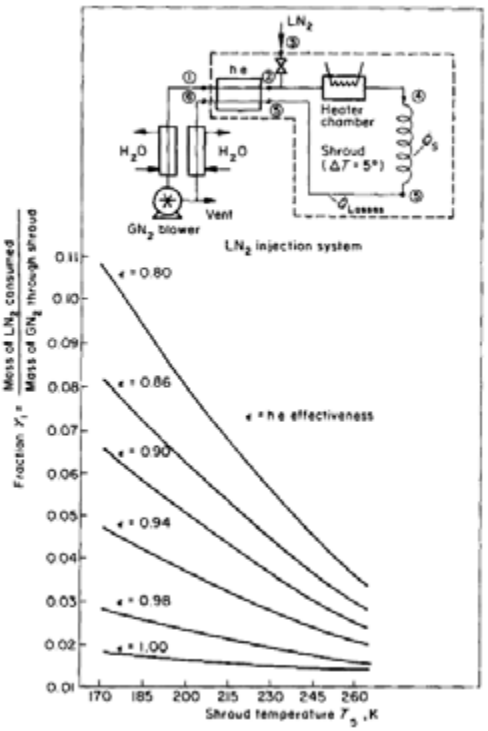

Fig. 1 Bypass fraction χ as a function of shroud temperature T_5

through the LN_2 bath and the other around it, making an enthalpy balance before and after mixing, we get

$$xh_3 + (1 - x)h_2 = h_4$$

or

$$x = (h_2 - h_4)/(h_2 - h_3) \quad (1)$$

Equation (1) tells us what fraction of the total mass flow that should pass through the LN_2 bath to get the required shroud temperature. This is important for the selection of the appropriate control valves.

Since we have fixed $T_3 = 95$ K, h_3 is fixed. Then, for a given shroud inlet temperature T_4 ie for a given h_4, x depends upon h_2 (or T_2). Now, it is clear that T_2 depends upon the heat exchanger effectiveness, ϵ. We can write

$$T_2 - T_5 = (1 - \epsilon)(T_1 - T_5)$$
$$T_5 = T_4 + 5$$

Also

$$(h_2 - h_4) = \bar{c}_{p,\,2\text{-}4}(T_2 - T_4),$$

and

$$(h_2 - h_3) = \bar{c}_{p,\,2\text{-}3}(T_2 - T_3)$$

Substituting in equation (1), we get

$$x = \bar{c}_{p,\,2\text{-}4}[(1 - \epsilon)(T_1 - T_5) + 5]/\bar{c}_{p,\,2\text{-}3}[(1 - \epsilon)T_1 + \epsilon T_5 - T_3] \quad (2)$$

Equation (2) was solved using a BESM-6 russian computer for various values of shroud temperature (T_5) and heat exchanger effectiveness, (ϵ). Results are plotted in Fig. 1.

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During the hot cycle (300 K-373 K) the entire gas stream coming from the heat exchanger bypasses the LN_2 bath and goes through a heater chamber before entering the shroud. By controlling the power input to the electrical heaters, temperature of the gas entering the shroud is controlled. As in the previous case, the return gas from the shroud travels to the suction of the blower via the heat exchanger, thus preheating the incoming gas stream.

In analysing the system we made the following assumption: ΔT across the shroud = 5 degrees; temperature of the gas stream immediately after passing through the LN_2 bath is 95 K, this ensures that the GN_2 does not liquefy; total heat load on the shroud comprises radiation from the chamber wall plus conduction through supports (at 10% of radiation) and constant dissipation from specimen placed inside the chamber (50W).

Now, referring to Fig. 1 (inset), let us define two dimensionless factors as follows:

$$x = \text{Bypass fraction} = \frac{\text{mass flow rate of } GN_2 \text{ through the } LN_2 \text{ bath}}{\text{mass flow rate of } GN_2 \text{ through the shroud}}$$

$$Z = \frac{LN_2 \text{ consumption rate}}{\text{mass flow rate of } GN_2 \text{ through the shroud}}$$

Bypass fraction x: Since the temperature at the inlet to the shroud is obtained by mixing two streams of gas, one passing

Fraction Z. Liquid nitrogen is boiled off in the LN_2 bath in the process of cooling that fraction of the total mass flow which passes through the bath. Equating the enthalpy lost by the gas stream to that gained by the LN_2, we get

$$z = x(h_2 - h_3)/h_{fg}$$

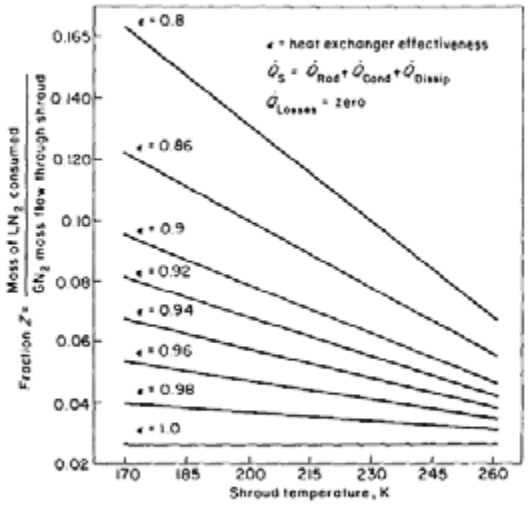

ε = heat exchanger effectiveness
$\dot{Q}_S = \dot{Q}_{Rad} + \dot{Q}_{Cond} + \dot{Q}_{Dissip}$
$\dot{Q}_{Losses}$ = zero
ε = 0.8
ε = 0.86
ε = 0.9
ε = 0.92
ε = 0.94
ε = 0.96
ε = 0.98
ε = 1.0
Fraction Z = Mass of LN_2 consumed / GN_2 mass flow through shroud
Shroud temperature, K

Fig. 2 Fraction Z as a function of shroud temperature T_S

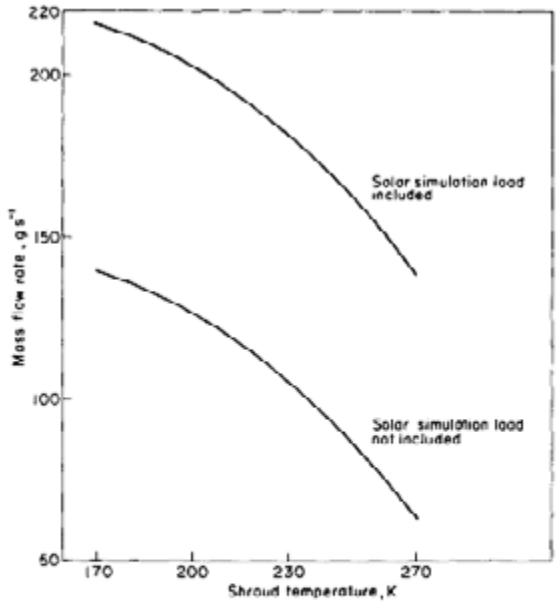


Fig. 3 2 m diameter thermovac chamber. Mass flow rate through shroud Vs shroud temperature

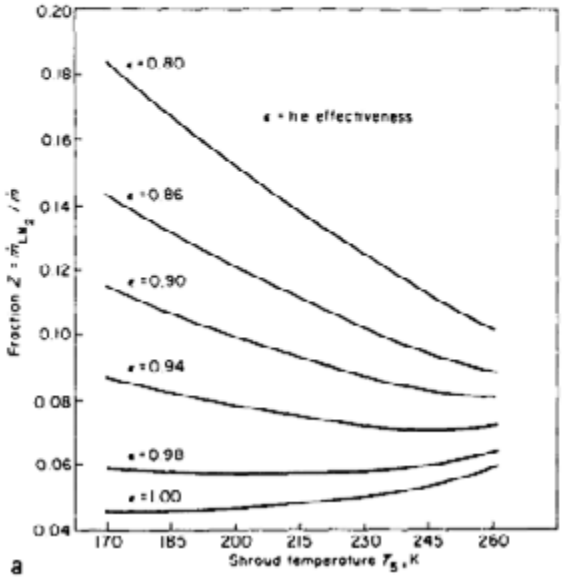
But, from (1) and (2),

$$x(h_2 - h_3) = (h_2 - h_4) = \bar{c}_{p,\,34}[(1-\epsilon)(T_1 - T_4) + 5]$$

In the above analysis, heat loss to the lines, $\dot{Q}_L$, was assumed to be zero. However, if these losses are also taken into account, applying the I law to all the components of the system, excepting the blower, (Fig. 1, inset), we get,

$$\dot{Q}_S + \dot{Q}_L = \dot{m}(h_6 - h_1) + \dot{m}_{LN2} h_{fg}$$

where $\dot{m}$ = mass flow rate of GN_2 through the shroud and $\dot{m}_{LN2}$ = LN_2 evaporation rate in the LN_2 bath.



a

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and we can write,

$$z = \bar{c}_{p,\,24}\,[(1-\epsilon)(T_1 - T_5) + 5]/h_{fg} \qquad (3)$$

Equation (3) has also been solved using a computer. Results which show z as a function of shroud temperature (T_5), for various values of heat exchanger effectiveness are plotted in Fig. 2.

Massflow rate through the shroud ($\dot{m}$). $\dot{m}$ is given by

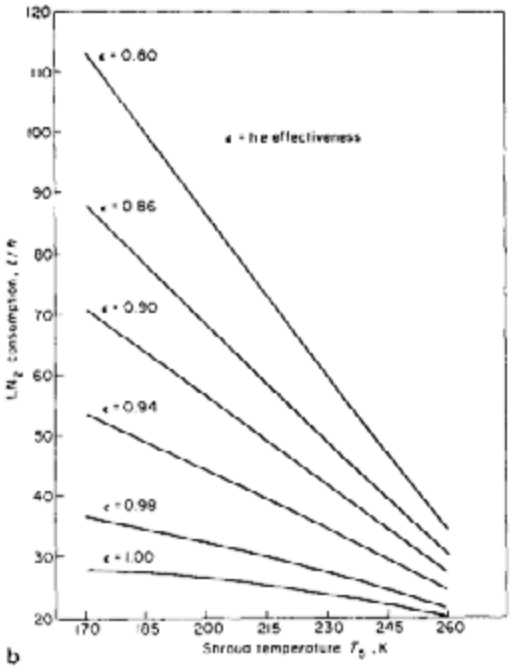
$$\dot{m} = \frac{\text{Heat load on the shroud}}{c_p \Delta T}$$

where ΔT is the temperature difference across the shroud. In Fig. 3, $\dot{m}$ is plotted as a function of shroud temperature, with $\Delta T = 5$ degrees, for the case of 2.0 m diameter tvc. Upper curve shows the variation of mass flow rate with shroud temperature when the solar simulation load is included in addition to other loads. The lower curve is for the case where the solar simulation load is not included.

LN_2 consumption. LN_2 consumption can be calculated using Fig. 2 and Fig. 3. At a given shroud temperature and he effectiveness, fraction Z is read off from Fig. 2, and the value of $\dot{m}$ from Fig. 3. Then, amount of LN_2 consumed

$$= z\dot{m}\ \mathrm{g\,s^{-1}}$$
$$= (4.5)(z\dot{m})\ \mathrm{l/h} \qquad (4)$$

Equation (4) was solved on a computer and LN_2 consumption for the 2.0 m diameter tvc as a function of shroud temperature for various values of he effectiveness is shown in Fig. 4.



b

Fig. 4 2.0m diameter thermovac chamber (gas bypass flow system). a – fraction Z as a function of shroud temperature T_5 (Note: $\dot{Q}_S = \dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{DISSIP.}$ $\dot{Q}_{LOSSES} = 500$ W); b – LN_2 consumption as a function of shroud temperature

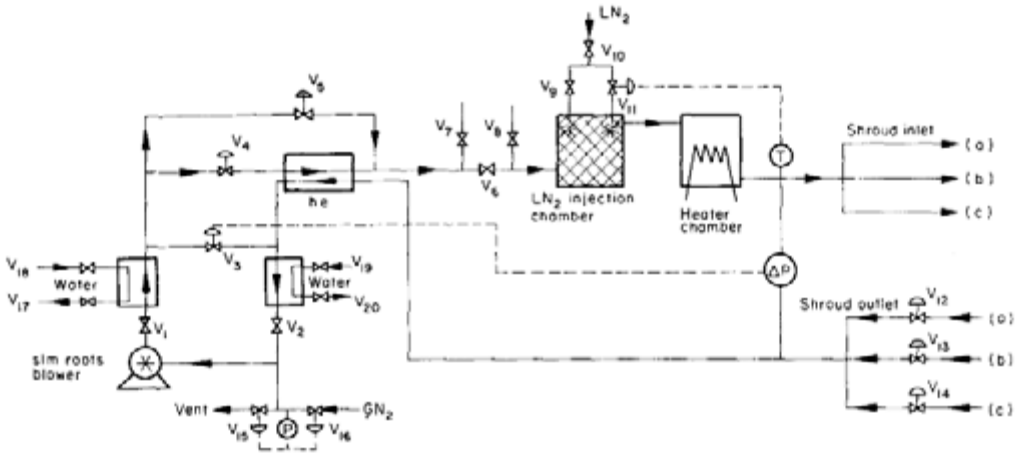


Fig. 5 LN_2 injection system

or

$$Z = \dot{m}_{LN2}/\dot{m}$$
$$= (\dot{Q}_s + \dot{Q}_L)/\dot{m}h_{fg} + (h_1 - h_6)/h_{fg}$$

But,

$$(h_1 - h_6) = \bar{C}_{p,\,1-6}(T_1 - T_6)$$
$$= \bar{C}_{p,\,1-6}(1-\epsilon)(T_1 - T_5)$$

water cooled preheater, where the GN_2 stream is warmed back to room temperature, and then to the blower suction.

During the hot cycle, LN_2 injection is switched off and the GN_2 stream coming from the he is heated in the heater chamber by activating the electrical heaters. Now, the temperature at the inlet to the shroud is controlled within

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$$\therefore Z = (\dot{Q}_s + \dot{Q}_L)/\dot{m}h_{fg} + \bar{C}_{p,1-6}(1-\epsilon) \times (T_1 - T_5)/h_{fg} \quad (5)$$

And, amount of LN_2 consumed

$$= Z\dot{m}, \text{ g s}^{-1}$$

$$= (4.5)(Z\dot{m}), \text{ l/h} \quad (6)$$

Equations (5) and (6) were computed with $\dot{Q}_L$ = 500 W and the results are plotted in Fig. 4a and Fig. 4b.

Liquid nitrogen injection system

The system is shown in Fig. 5. As in the gas-bypass flow system, it consists of a GN_2 blower, heat exchanger, heater chamber, shroud and necessary valves and piping. The LN_2 bath is replaced by a LN_2 injection chamber where LN_2 is injected into the GN_2 stream coming from the heat exchanger. This is the type of system used for the isa space simulation chamber in Ottobrunn (iabg), Germany.[2] The GN_2 blower compresses GN_2 from 2.03×10^3 kN m^{-2} to 3.04×10^2 kN m^{-2}. Heat of compression is removed in the aftercooler. There is another precooler just before the suction of the blower. This ensures that the GN_2 only enters the blower at room temperature, in both the heating and cooling cycles. During the cold cycle the GN_2 stream at 3.04×10^2 kN m^{-2} passes through the aftercooler and is precooled in the heat exchanger before being led on to the LN_2 injection chamber. Here, LN_2 is injected from the top into the GN_2 stream coming from below. The resultant cold GN_2 stream passes on to the shroud through the heater chamber which remains inactive during the cold cycle. The temperature at the inlet of the shroud is controlled within ± 1 degree by controlling the LN_2 injection rate. The return-stream from the shroud passes through the heat exchanger where it precools the incoming GN_2 stream, the

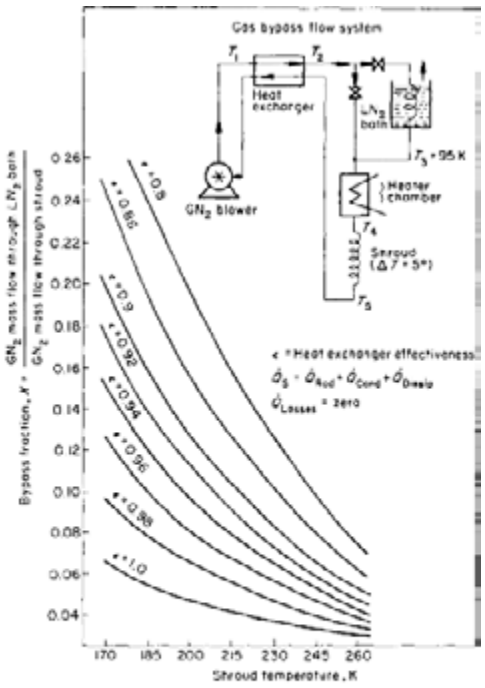
Gas bypass flow system
Heat exchanger
LN2 bath
GN2 blower
Heater chamber
Shroud (ΔT = 5°)
T3 = 95 K
ε = Heat exchanger effectiveness
Q̇S = Q̇Rad + Q̇Cond + Q̇Dissip
Q̇Losses = zero
GN2 mass flow through LN2 bath / GN2 mass flow through shroud
Bypass fraction, x
Shroud temperature, K

Fig. 6 2.0 m diameter thermovac chamber: fraction Y_1 as a function of shroud temperature (Note: $\dot{Q}_S = \dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{DISSIP}$, $\dot{Q}_{LOSSES}$ = ZERO)

± 1 degree by controlling the power input to the heaters. As in the previous case, the return GN_2 stream from the shroud passes through the he where it pre-heats the incoming GN_2 stream, and then to the water cooled precooler, where the GN_2 stream gets cooled to room temperature, and then to the blower suction.

In analysing the system the following assumptions were made: ΔT across the shroud = 5 degrees; total heat load on the shroud consists of radiation from chamber walls plus conduction through supports (at 10% of radiation) and constant dissipation from the specimen placed inside the chamber (= 50 W); other external heat leaks to the system such as heat leak to the transfer lines, LN_2 injection chamber, heat exchangers etc, are also considered.

With reference to Fig. 6 (inset) let us apply the I law to the whole of thermal system except the GN_2 booster and its pre-cooler and after-cooler. Let the external heat leak through the boundary (shown in dotted lines) be $\dot{Q}_L$ W.

According to the I Law,[3]

$$\dot{Q} - \dot{W} = \sum_{\text{outlets}} \dot{m}h - \sum_{\text{inlets}} \dot{m}h$$

(Heat flowing into the system is + ve; work done by the system is + ve)

$$\therefore \dot{Q}_{\text{shroud}} + \dot{Q}_L + 0 = \dot{m}_6 h_6 - (\dot{m}_1 h_1 + \dot{m}_3 h_3)$$

$$= \dot{m}_6 h_6 - (\dot{m}_6 - \dot{m}_3)h_1 - \dot{m}_3 h_3, \quad \text{since } \dot{m}_6 = (\dot{m}_1 + \dot{m}_3)$$

$$= \dot{m}_6(h_6 - h_1) + \dot{m}_3(h_1 - h_3)$$

or

$$\dot{m}_6(h_1 - h_6) + \dot{Q}_L = \dot{m}_3(h_1 - h_3)$$

Now, define $y = (\dot{m}_3/\dot{m}_6)$

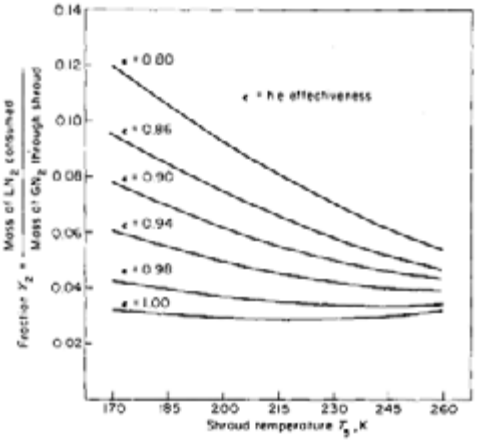
ε = 0.80
ε = 0.86
ε = 0.90
ε = 0.94
ε = 0.98
ε = 1.00
ε = he effectiveness
Fraction Y2 = Mass of LN2 consumed / Mass of GN2 through shroud
Shroud temperature Ts, K

Fig. 7 2.0m diameter thermovac chamber: fraction Y_2 as a function of shroud temperature (Note: $\dot{Q}_S = \dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{DISSIP}$, $\dot{Q}_{LOSSES}$ = 500 W)

For $\dot{Q}_L = 0$, amount of LN_2 consumed $= y_1\dot{m}$ g s^{-1}

$$= (4.5)y_1\dot{m} \text{ l/h} \quad (10)$$

and for $\dot{Q}_L$ = 500 W, amount of LN_2 consumed

$$= y_2\dot{m} \text{ g s}^{-1}$$

$$= (4.5)y_2\ \dot{m} \text{ l/h} \quad (11)$$

Equations (10) and (11) were also computed and the results are shown plotted in Figs 8 and 9. For both these case shown solar load was taken as zero.

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= (mass rate of LN_2 consumed)/(mass rate of GN_2 flowing through shroud)

$$\therefore y = (h_1 - h_6)/(h_1 - h_3) + (\dot{Q}_s + \dot{Q}_L)/\dot{m}_6(h_1 - h_3) \quad (7)$$

Substituting $(h_1 - h_6) = \bar{c}_{p,1-6}(T_1 - T_6)$ and heat exchanger effectiveness $\epsilon = (T_1 - T_2)/(T_1 - T_6)$ we get,

$$y = [\bar{c}_{p,1-6}(T_1 - T_5)(1 - \epsilon) + (\dot{Q}_s/\dot{m}_6) + (\dot{Q}_L/\dot{m}_6)]\,/\,[(h_1 - h_3) - \bar{c}_{p,1-6}\epsilon(T_1 - T_5)] \quad (8)$$

and when $\dot{Q}_L = 0$,

$$y = [\bar{c}_{p,1-6}(T_1 - T_5)(1 - \epsilon) + (\dot{Q}_s/\dot{m}_6)]\,/\,[(h_1 - h_3) - \bar{c}_{p,1-6}\epsilon(T_1 - T_5)] \quad (9)$$

In equations (8) and (9), we have $T_1 = 300$ K and T_5 is the shroud temperature. Therefore, h_1, enthalpy of GN_2 at 3.04×10^2 kN m^{-2} and 300 K and h_3, enthalpy of LN_2 at 3.04×10^2 kN m^{-2} are fixed. These equations were computed and the results plotted in Figs 6 and 7. In Fig. 6, y is plotted as a function of T_5 for $\dot{Q}_L = 0$ and in Fig. 7, y is plotted as a function of T_5 for $\dot{Q}_L = 500$ W, for various values of ϵ.

LN_2 consumption. When $\dot{Q}_L = 0$, LN_2 consumption can be calculated using Fig. 3 and Fig. 6 and when $\dot{Q}_L = 500$ W, LN_2 consumption can be calculated using Fig. 3 and Fig. 7.

Heater power requirements

During the hot cycle operation of both the systems considered, the hot return stream from the shroud preheats the GN_2 stream entering the heater chamber, in the heat exchanger. Therefore, it is clear that at a given shroud temperature the heater power required depends upon the he effectiveness.

Referring to Fig. 6 (inset), let us apply the I law to the system consisting of the heater chamber and the shroud only. If the heat loss from the shroud is $\dot{Q}_s$ W (including radiation and conduction at 10% of radiation) and the heater power required is $\dot{Q}_H$ W, we can write, neglecting the losses in the lines,

$$(\dot{Q}_H - \dot{Q}_s) = \dot{m}(h_5 - h_2) = \dot{m}\bar{c}_{p,2-5}(T_5 - T_2) = \dot{m}\bar{c}_{p,2-5}(1 - \epsilon)(T_5 - T_1)$$

$$\therefore \dot{Q}_H = \dot{Q}_s + \dot{m}\bar{c}_{p,2-5}(1 - \epsilon)(T_5 - T_1) \quad (12)$$

Now, between room temperature and 375 K we can assume $\bar{c}_{p,2-5}$ to be constant = 1.03 J g^{-1} K^{-1}. At a given T_5, from (12), we can write,

$$(\mathrm{d}\dot{Q}_H/\mathrm{d}\epsilon)|_{T_5 = \text{const.}} = -\dot{m}\bar{c}_{p,2-5}(T_5 - T_1) \quad (13)$$

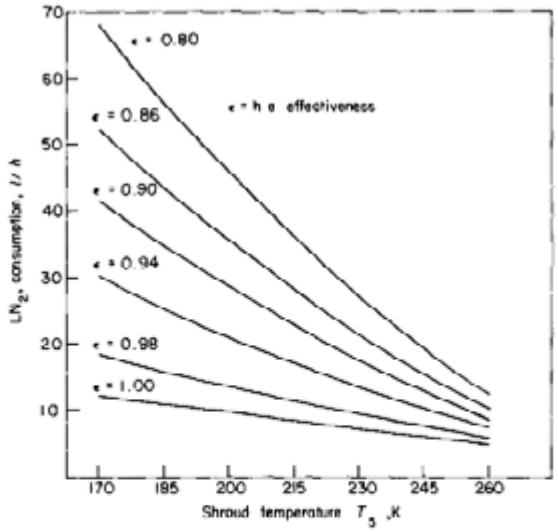

Fig. 8 2.0m diameter thermovac chamber: LN_2 consumption as a function of shroud temperature (Note: $\dot{Q}_S = \dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{DISSIP}$, $\dot{Q}_{LOSSES}$ = ZERO)

Discussion and comparison of the two systems

Bypass fraction x. In the first system considered, the amount of GN_2 that should pass through the LN_2 bath is expressed as a fraction of the amount of GN_2 passing through the shroud. For a given shroud (ie for a given thermovac chamber) at a given temperature, the amount of GN_2 passing through the shroud is fixed for a given ΔT. If we examine (2), we see that x depends only on T_5 and ϵ for given T_1, T_3. Therefore, the curves of Fig. 1 are universally applicable for any thermovac chamber for a particular value of T_1 and T_3 as assumed here.

Fraction z. The LN_2 consumption is also given as a fraction of the amount of GN_2 flowing through the shroud. From the reasoning given above, it is clear that the curves for z, as shown in Fig. 2, are also applicable for any tvc under identical conditions of T_1, T_3. However, the curves in Fig. 4a are not universally applicable since the factor $(\dot{Q}_L/\dot{m}h_{fg})$ occurs in (5) and the value of $\dot{m}$ would be different for different tvc's;

Fraction y. LN_2 consumption for the LN_2 injection system is also expressed as a fraction of the amount of GN_2 passing through the shroud. If we examine (9) for y with $\dot{Q}_{losses}$ = zero, since $(\dot{Q}_s/\dot{m}_6) = \bar{c}_{p,4-5}.\Delta T$, we find that value of y depends only on T_5 and ϵ for given values of T_1 and T_3. Therefore, the curves for y as shown in Fig. 6 should be

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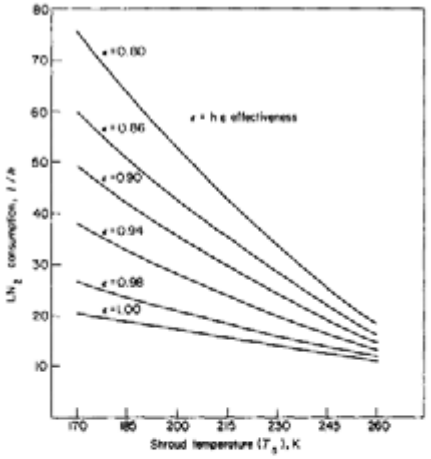

Fig. 9 2.0 m diameter thermovac chamber: LN_2 consumption as a function of shroud temperature (Note: $\dot{Q}_S = \dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{DISSIP}$, $\dot{Q}_{LOSSES} = 500W$

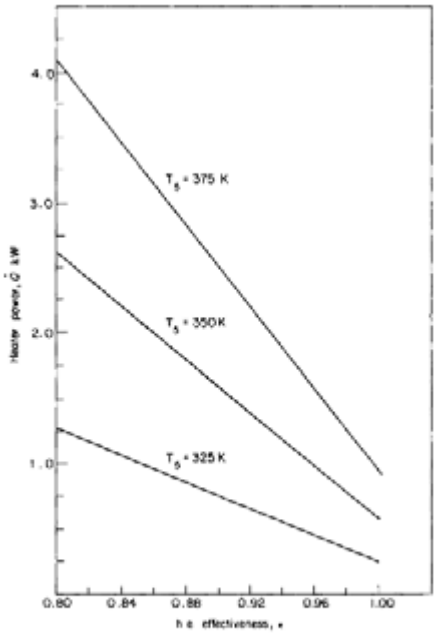

Fig. 10 2.0 m diameter thermovac chamber: heater power vs he effectiveness (Note: $\dot{m}_{GN_2}$ = 200 gs^{-1})

ie at a given shroud temperature T_s, the plot of heater power required, Q_H, against he effectiveness, ϵ, is a straight line of negative slope, the value of slope is given by (13).

Fig. 10 shows such a plot for T_s = 325 K, 350 K and 375 K. At these values of T_s, corresponding values of $\dot{Q}_S$ are 255 W, 575 W and 960 W with emissivity of copper surface = 0.1 and that of SS = 0.2. Value of $\dot{m}$ is kept constant at 200 g s^{-1}.

universally applicable for any tvc, for given values of T_1 and T_3. However, when $\dot{Q}_L$ is included, the curves as shown in Fig. 7, are not universally applicable since the factor $(\dot{Q}_L/\dot{m}_6)$ occurs in (8) and $\dot{m}_6$ would obviously be different for different tvc's.

Liquid nitrogen consumption

Calculated values of LN_2 consumption for the 2.0 m diameter tvc using system I and system II have been plotted respectively in Figs 4 and 8 with $\dot{Q}_L = 0$ and in Figs 4b and 9 with $\dot{Q}_L$ = 500 W. It is clear from these figures that the higher the value of he effectiveness, ϵ, at a given shroud temperature, the lower is the value of LN_2 consumption. Let us compare the two systems at a given value of ϵ, say ϵ = 0.86 and given values of T_s = 170 K to 260 K, as shown in Table 1.

It can be seen that LN_2 consumption is lower for the LN_2 injection system as compared to the gas-bypass flow system. Saving in LN_2 with the LN_2 injection system varies from 31.7% at 170 K to 46.9% at 260 K, for ϵ = 0.86 and $\dot{Q}_L$ = 500 W. Therefore, it is clear that the LN_2 injection system is to be adopted.

Components of the thermal system

The shroud, 1.8 m diameter and 2.3 m long, is made of extruded copper tube-fin sections, placed in a Chevron array. Suitable stainless steel headers at both ends ensure that the pressure drop in the shroud is not excessive. The shroud is painted black from inside with space-quality paint and the outside surface is electropolished for low emissivity. Vacuum insulated feedthroughs conduct the GN_2 stream into and out of the chamber.

A Hampson type of heat exchanger was designed for the system. It has a total surface area of 25 m^2 with copper tubes (8 mm id x 10 mm od) arranged in ten layers, each layer containing eight tubes wound helically on a mandrel. The high pressure stream passes through the tubes and the low pressure stream flows across the tubes. The measured value of he effectiveness, taken during the preliminary trials on the thermovac chamber, is 0.85.

The injection chamber is an ss chamber (0.5 m diameter x 0.75 m long) filled with ss wool. LN_2 is injected from the top and GN_2 flows from below.

The heater chamber is also an ss chamber (0.5 m diameter x 0.75 m long). It has four heaters (each of 1.5 kW capacity) fixed from the top-dish. A temperature controller controls the temperature at the shroud inlet by controlling the power supplied to the heaters.

A blower, to circulate 250 g s^{-1} of GN_2 was selected (Model RP-40 of M/s. Sim-Manekial). Suction pressure is 2.03×10^2 kN m^{-2} and discharge pressure is 3.04×10^2 kN m^{-2}. The blower is complete with a silencer and two water coolers, one at the inlet and the other one at the outlet. The inlet cooler ensures that the GN_2 entering the blower is at room temperature (300 K) and outlet cooler ensures that GN_2 entering is the he is at 300 K.

All piping except between the he and GN_2 blower are of stainless steel, insulated with fibre glass. Between the blower and he piping is of mild steel.

Conclusion

Both the thermovac chambers designed have now been installed successfully. Preliminary trials have been taken and it is found that the results conform to the designs, generally.

I wish to express my appreciation to my colleague, Shri M. Pravin Kumar, who did the computer programming. Thanks are also due to Shri M.R. Vyawahare for his help during the design of heat exchangers.

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Note: Entire design and drawings for these chambers were supplied by Bhabha Atomic Research Centre, Bombay and the fabrication was undertaken by M/s. Indo Burma Petroleum Co., Bombay.

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Table 1. LN_2 consumption, l h^{-1}, $\epsilon = 0.86$, $T_1 = 300$ K

System \ T_5, K	170	185	200	215	230	245	260
Gas-bypass flow system ($\dot{Q}_L$ = 500 W)	87.8	78.5	69.0	59.0	49.0	39.4	30.5
LN_2 injection system ($\dot{Q}_L$ = 500 W)	60.0	51.1	42.8	35.0	28.0	21.7	16.2
Saving in LN_2 with LN_2 injection system, %	31.7	34.9	38.0	40.7	42.9	44.9	46.9

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